

Performance optimization of multimedia services in wireless multimedia sensor networks (WMSN) at the socket level

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KEY WORDS	ABSTRACT
Quality of Service (QoS) Wireless Multimedia Sensor Networks (WMSN) Socket-level Communication Priority Scheduling High Data Rate Traffic	Wireless Multimedia Sensor Networks (WMSNs) can collect video, audio, and scalar data, making them highly valuable for Internet of Things (IoT) applications. There is a growing demand for improved Quality of Service (QoS) in WMSNs, particularly in terms of energy efficiency, latency, and reliability. Meeting these requirements poses significant challenges, as researchers must develop methodologies that optimize resource utilization, enhance QoS and network performance, and minimize packet loss. QoS enhancements can be achieved at various layers of a WMSN from the Application layer down to the Physical layer. In this research, we implement priority schemes tailored for high data rate scenarios; packet traffic follows burst arrival and departure patterns. Our results show that assigning dedicated sockets on a single channel and prioritizing video and voice packets can significantly improve the QoS of the network. The simulation results clearly indicate that the single-channel sockets model outperforms the multichannel model across key performance metrics. In terms of throughput, the single-channel sockets scheme achieves approximately 10–12% higher values, showing its efficiency in handling increased traffic flows. Delay performance is also significantly improved, with about 15–20% lower latency under heavy load compared to the multichannel design. Furthermore, packet loss is reduced by nearly 10% in the initial phase, stabilizing at levels close to zero, thereby highlighting the robustness of the proposed single-channel sockets approach in supporting resilient and high-quality multimedia communication.

1. Introduction

Sensor networks, being the latest technology, are advancing rapidly, along with MEMS, embedded computing, and the accessibility of low-cost Complementary Metal Oxide semiconductors (CMOS) and multimedia cameras, which have caused considerable progress in source coding techniques for multimedia. The integration of wireless sensor networks into sensor nodes with visual and audio is a precursor to wireless multimedia sensor networks. WMSN can store, embed, and share data from different audio and visual sensors [1]. Multiple sensors

can improve data accuracy and efficiency by providing coverage of the application. Moreover, multiple visual sensors can provide adaptive data depending on the application requirements. Wireless multimedia sensor networks can be used as surveillance and monitoring systems, etc.

Many researchers discussed the effectiveness of IoT through managing real-time data, but hardly raised the issues related to WMSN [7, 8]. The need for the era of smart devices has enabled the world to view multimedia data and changed the direction of research

from conventional IoT [2, 3], hence the evolution in the field of the Internet of Multimedia Things (IoMT).

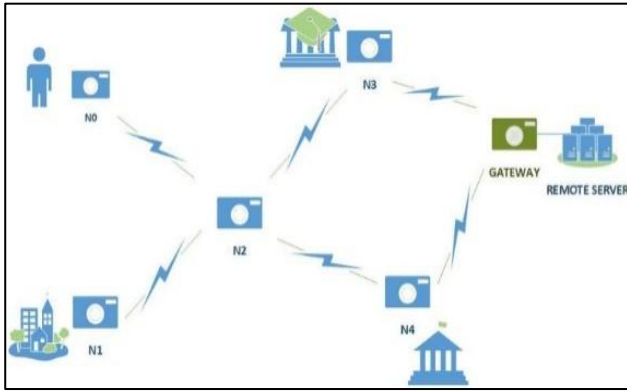


Fig 1. Multi Hop Wireless Multimedia Sensor Network

In the IoMT environment, the communication of multimedia data between devices needs a high amount of bandwidth, memory, and processing as compared to scalar data transmission. With the advent of multimedia transmission, military and commercial-level applications have been introduced to transmit maximum data.

Sensors in wireless multimedia sensor networks typically operate under low traffic loads and only become active in response to external triggers. These sudden events can generate a large amount of data in bursts, which are sent to sink nodes without degrading application performance. Such multimedia traffic can easily cause network congestion if not managed properly, leading to high delays, decreased throughput, and packet loss due to buffer overflows. To prevent these issues, effective network capacity management and data management are essential for maintaining both performance and battery efficiency. Rate-based traffic adaptation algorithms are especially important for handling bursty traffic. These algorithms enable nodes to become more intelligent and autonomous, supporting both resource management and QoS adjustment.

In this paper, we present an analytical approach for handling data packets that arrive and depart from sensor nodes in bursts. Section 2 presents the literature review related to quality-of-service challenges in wireless multimedia sensor networks, including priority packetization and transportation, as discussed by various researchers. Section 3 describes the proposed research methodology in detail. We explain the two-stage hyper-exponential model for bursty traffic, introduce the proposed priority schemes, and present analytical expressions for key performance measures. Section 4 discusses the results of the analytical model (implemented in MATLAB) and the simulation model (using NS-3). Section 5 concludes with a summary of the research findings and suggestions for future work.

2. Materials and Methods

Service (QoS), which includes reliable data transfer, high transmission rates, reduced error rates (to minimize retransmissions), and fewer dropped packets due to timeouts and other factors. Meeting these QoS requirements is essential to enhancing the overall performance of the network. In [5], a considerable amount of research has addressed energy-related issues in multimedia wireless sensor networks, aiming to maximize battery life and extend the operational lifespan of WMSN nodes. Zara Hamid et al. [6] and Jadoon et al. [7] have investigated the challenges of multimedia video transmission over wireless channels. Mounib Khanafer et al. [8] proposed the Receiver-Initiated (RI-MAC) protocol to improve the QoS of wireless sensor networks by refining communication protocols, reducing transfer delays, employing energy-efficient sensor nodes, and introducing various other techniques.

Furthermore, Zara Hamid et al. [6] and Khattak et al. [9] proposed cross-layer approaches to optimize multimedia packet communication while enhancing energy efficiency. In cross-layered WMSNs, every layer in the protocol stack plays a role in ensuring QoS. This approach addresses both significant delays and the high bandwidth demands of WSNs. Simiscuka et al. [10] introduced REMOS-IoT, an algorithm for IoT communications that improves QoS, relevance, and location-awareness. REMOS-IoT claims to reduce packet losses and delays, but it does not provide explicit priority handling for multimedia data.

M. Noman Hayat et al. [11] discussed multichannel interfacing architectures for WMSNs designed to meet maximum data rate demands. Their work identifies various channel policies, assignment strategies, and methods by classifying multichannel protocols. Junghye Kim et al. [12] proposed a queue-based algorithm that provides a traffic control mechanism to guarantee QoS in WMSNs. This mechanism consists of a packet marking algorithm and queue management, and it categorizes traffic into event-driven, query-based, multimedia, and periodic types. Packet marking determines the importance of each packet and prioritizes its transfer to the sink node, while queue management at the broadcasting node decides whether a packet should be delivered or forwarded based on the current queue occupancy.

Ismail et al. [13] introduced a cross-layer approach to handle video frames, assigning high priority to critical frames and lower priority to less important ones at the application layer. This approach improves the packet data rate, reduces delays, and minimizes packet loss. However, the authors do not address the scenario where frames are transmitted and processed

in bursts—a common occurrence with high data rates, where frames are sent, received, and processed in rapid succession.

Nidal Nasser et al. [14] presented an extensive survey of military and civil applications for WSNs, highlighting the constraints of battery-powered sensor nodes and the challenges of replacing or recharging them, especially in hostile environments or when the number of sensors is high. One of the most important aspects of wireless sensor networks is packet scheduling, which helps minimize power consumption and interruptions during data transmission. Several algorithms are used for scheduling, including First-Come-First-Served (FCFS), non-preemptive, and preemptive priority algorithms. However, most of the algorithms discussed above are not responsive to the dynamic requirements of WSNs, as their scheduling strategies are predetermined.

Xu, Y., Qi, et al. [15] proposed a priority-based queuing model based on M/M/1 queues and a Random Early Detection (RED) priority scheme. Their performance analysis demonstrates that RED policies can effectively control congestion and prioritize packets. Imen Bouazz et al. [16] presented a fuzzy logic controller-based algorithm, assigning priorities using queue length and traffic rate as fuzzy variables for a fuzzy priority model with an unreliable server. In their scheme, priority is assigned to nodes that wish to access the channel, with decisions based on the node's transmission rate and available bandwidth. This approach helps control buffer overflow and packet loss by putting nodes with high transmission rates on hold if the available bandwidth is insufficient.

In [17], Abbas N. et al. proposed an Intelligent Video Surveillance Platform (IVSP) for WMSNs. Their research introduces three queues: one for emergency packets and two for packets prioritized based on node location. The approach uses both buffer length and its rate of change to predict and detect congestion more accurately.

3. Proposed Materials and Method

3.1 Analytical Model

A statistical model is based on the proposed optimized performance scheme in [18] by T. K. Khan et al. The proposed model discusses two-stage hyper-exponential cyclic models. The Purpose of analyzing this model is to derive analytical expressions for calculating performance metrics, i.e., packet loss, utilization, etc., by taking the limit of the first branch of the recipient center and the first branch of the server center to infinity. To derive an analytical solution and traffic behavior, it is assumed that no packets leave without getting service when all the packets that arrive

at the sink node get the service, and the system becomes empty. Moreover, packets that arrive at the sink node and find all sockets busy are blocked and never sent back to the system again.

Because of high data rates, the packet/s arrivals at the sink node are in burst formation and subsequently are treated in bursts, following a Poisson distribution for service, whereas for arrival, they follow a generalized exponential distribution. The analytical model for processing, blocking, no. of packets in service, and arrival originated by implementing a limit of the 1st receiver branch and server to infinity of 2 2-stage hyper exponential methods.

Packets that arrive at the system can select either the 2nd branch with probability of $1-\sigma$ or σ 1st branch with probability of $1-\gamma$ or γ respectively, as shown in Fig. 2a and 2b.

Where σ is the mean number of bulk arrivals, γ is the mean number of bulk departures, λ is the Mean arrival rate, and μ is the Mean Service rate.

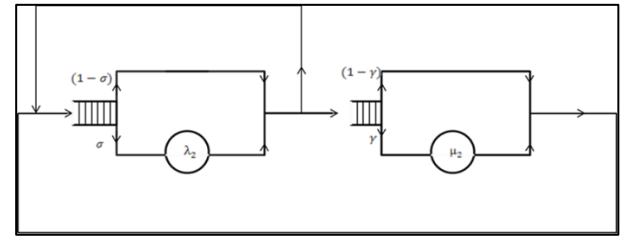


Fig 2a. Two-stage hyper-exponential model for bursty arrivals in WMSNs. Arrivals follow a generalized exponential distribution; service is batch Poisson. Parameters: $\lambda = 10$ Mbps, $\mu = 12$ Mbps.

If the queue is full and additional packets arrive for service, these packets are blocked and will not re-enter the system for service. At the sink node, the arrival and departure of packets occur in bursts due to the high intensity of traffic. The service of packets follows a batch Poisson distribution, while their arrival at the sink node follows a generalized exponential distribution.

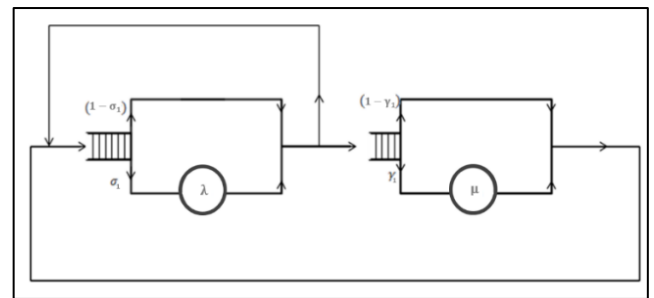


Fig. 2b Two-stage hyper-exponential model showing client waiting states. Blocked arrivals occur when all sockets are busy.

$$\lambda \xrightarrow{\text{tends}} \infty \quad \& \quad \mu \xrightarrow{\text{tends}} \infty$$

There are three waiting clients in this model. If any client is in the service of the receiver's exponential

branch, then the next client must wait in a queue. No two clients can get service at the same time. The same applies on the server side. The State transition diagram is explained in [18].

3.2 Priority Scheme for Bursty Traffic

The simulation is constructed using NS-3, as described in the analysis section, and employs the same parameters and behavior as the analytical model. Both single-channel systems with multiple sockets and multichannel systems with multiple sockets are evaluated. Priority and non-priority schemes are compared to assess the QoS improvements in terms of packet loss, waiting time, and throughput. Additionally, the simulation results are compared with the analytical results to validate the credibility of the analytical model.

A priority scheme has been developed by assigning dedicated sockets on a single channel specifically for video and voice calls. In addition, there are shared sockets where data, voice, and video packets can receive service, as illustrated in Fig. 3.

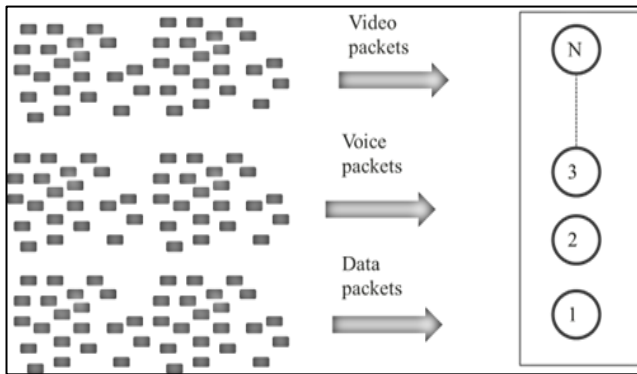


Fig 3. Simulation Model Diagrammatic View

When all shared sockets are occupied, any new data packets arriving for service will be blocked. There are also sockets dedicated to accepting voice and video packets; if these sockets are busy, the arriving voice packets will be blocked. Furthermore, there are sockets reserved exclusively for video packets. If all these sockets are busy, any incoming video calls will also be blocked.

Additionally, a scenario is considered in which queue is available for video calls, allowing video packets to wait when all video sockets are busy. The OFDMA channelization technique is used to manage the channelization of the medium.

3.3 Multichannel Multi-Socket Priority Model for Wireless Multimedia Sensor Networks

In Fig. 4, the basic simulation model for burst traffic in NS-3 is illustrated. In this model, we consider a total of five channels: three shared channels handle video, audio, and text data; the fourth channel is dedicated to both voice and video packets; and the fifth

channel is reserved exclusively for video packets. When all shared channels are busy, incoming data packets are blocked. Similarly, if the dedicated channels for voice and video are occupied, new voice packets will be blocked, and if all channels are busy,

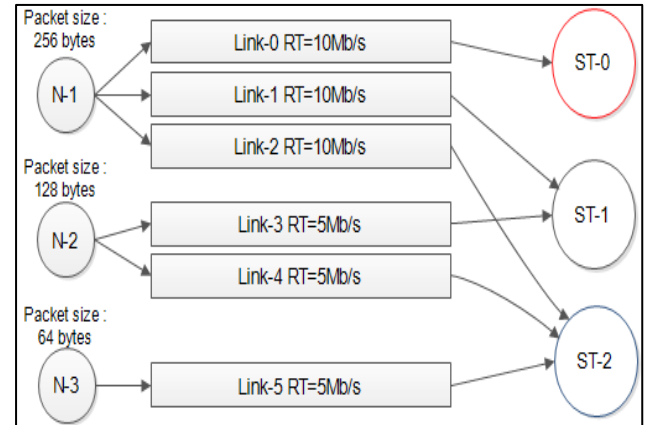


Fig 4. Multichannel Priority Model

The flowchart shown in Fig. 5 represents the design used in the simulation model. In this figure, T stands for traffic, while A, V, and N denote audio, video, and the number of nodes, respectively. The flow chart can be understood in two parts: the right side and the left side. The right side is responsible for initializing and defining the channels, as well as specifying the type of traffic each channel is configured to process or handle. It is important to note that while defining and setting up several channels, the connection is also established. All the channels are allocated individual IP addresses.

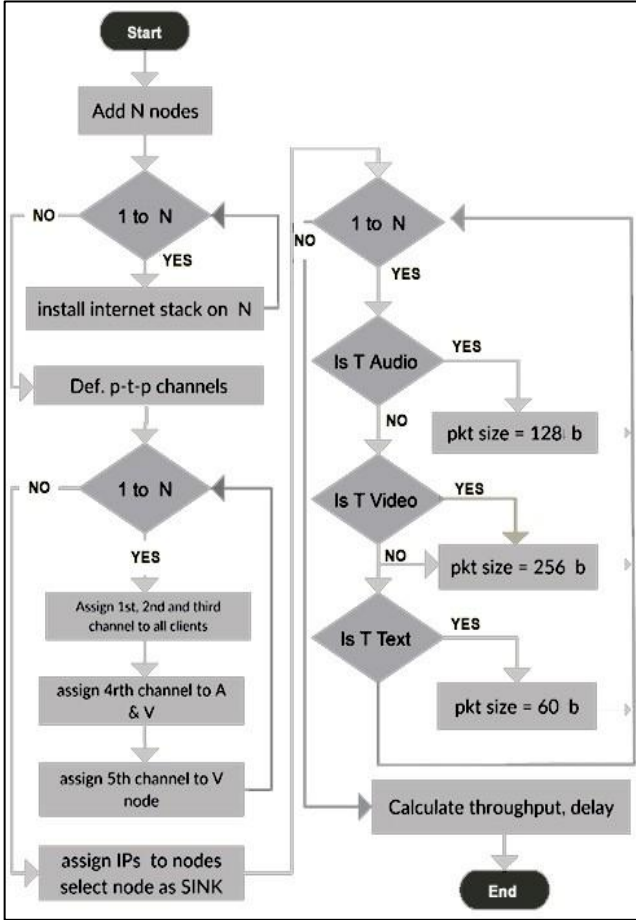
In the second part, which is the left side of the flowchart, the data packet sizes for text, voice, and video are defined. This enables the channels to identify the packet type for appropriate processing and prioritization. Finally, performance measures are calculated based on the simulation results.

In the proposed model (Fig. 5), priority is assigned to voice and video packets over data packets. The simulation includes three packet-generating nodes. Node “N-1” generates video packets of 256 bytes at a rate of 10 Mbps, and these packets are handled by Base Stations 1 and 2. Node “N-2” generates voice packets of 128 bytes at 5 Mbps. Similarly, Node “N-3” produces data packets of 64 bytes at 5 Mbps, as detailed in Table 1. The service stations—labeled “ST-2”, “ST-1”, and “ST-0”—are responsible for managing video, voice, and data packets, respectively. Video packets are managed by all three service stations (ST-1, ST-2, and ST-3), while voice packets are managed only at ST-1 and ST-2. Data packets, on the other hand, are managed only at ST-2. The detailed parameters of this model are provided in Table 1.

Table 1

Simulation Parameters for multi-channel priority model

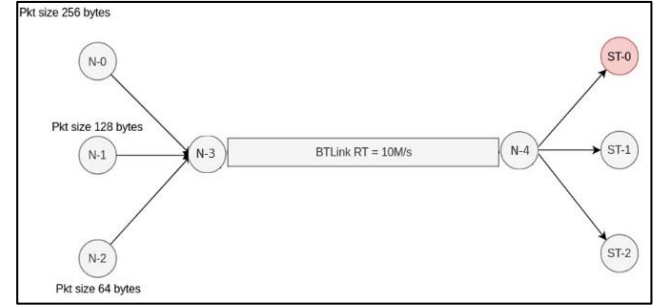
Client Node	Traffic type	Packet size bytes	Data rate mbps	ns3::Queue size packets	Priority	Base stations	Max Packets
N0	Video	256	10	5000	1	ST-0 ST-1 ST-2	5000
N1	Audio	128	5	2500	2	ST-1 ST-2	5000
N2	Data	64	5	1250	3	ST-2	5000

**Fig 5.** Flow diagram of the multichannel priority model. Video (256 B @ 10 Mbps), voice (128 B @ 5 Mbps), and data (64 B @ 5 Mbps) traffic are defined across multiple channels.

NS-3 Simulation Algorithms for Multichannel Priority Model: The priority model simulation has been performed in NS-3, where the computing device is called node δ . Each node can be connected through the channel CH . Network devices are installed to enable communication between channels and involve a software controller and simulated hardware. Thus, any node δ can be linked with one or more channels $CH(n)$ through limited network devices $\delta \xrightarrow{CH} \varepsilon$. The node protocol stack is configured and connected in this simulation.

3.4 Single-Channel Multi-Socket Priority Model for Wireless Multimedia Sensor Network

In the priority model for a single channel, voice and video packets are given higher priority than data packets. The simulation employs three packet-generating nodes. Node “N-1” generates video packets with a size of 256 bytes at a rate of 10 Mbps; these video packets are managed by Base Stations 1 and 2. Node “N-2” generates voice packets of 128 bytes at 5 Mbps, while Node “N-3” produces data packets of 64 bytes at 5 Mbps, as summarized in Table 1. The service stations—labelled “ST-2”, “ST-1”, and “ST-0”—are responsible for managing video, voice, and data packets, respectively. Video packets are processed by all service stations, voice packets are managed by “ST-1” and “ST-2” only, and data packets are managed exclusively at ST-2, as detailed in Table 3.3(a).

**Fig 6.** Single-channel multi-socket priority model. Video, voice, and data packets use separate sockets with priority.

Algorithm 1 , Phase 1: Setting up

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 $\delta_s$  = Server Node
 $\delta_c$  = Client Node
 $\delta_n$  = 'n' no. of nodes // which is 3 in this case
 $\alpha$  = adjacent node
 $\eta_n$  = 'n' no. of helper point to point instance
 $\varepsilon$  = no. of NetDeviceContainer :install network stack on nodes
for i = 1 to  $\delta_n$  do
   $\alpha(i) \leftarrow \text{NodeContainer}(\delta_s(i), \delta_c(i))$ 
end
for i = 1 to  $\eta_n$  do
  if i = 1 then  $\eta_1 \leftarrow \text{Highest DataRate and DropTailQueue(Pkts)}$ 
  end
  else if i = 2 then  $\eta_2 \leftarrow 2^{nd} \text{ Highest DataRate and DropTailQueue(Pkts)}$ 
  end
  else if i = 3 then  $\eta_3 \leftarrow 3^{rd} \text{ Highest DataRate and DropTailQueue(Pkts)}$ 
  end
for i = 1 to  $\varepsilon$  do
  if i = 1 then  $\varepsilon_i \leftarrow \text{Install.}(\eta_i)$ 
  end
end

```

In the proposed model (Fig. 6), priority is assigned to video and voice packets over data packets within a single channel. In this configuration, the client communicates with the base station using three separate sockets: socket 1 for video, socket 2 for audio, and socket 3 for data packets. Upon arrival at the

are used. The efficiency of the proposed model is determined by analyzing the results obtained for these performance metrics.

4.1. Packet Loss

Packet loss refers to the number of packets dropped by buffer nodes during transmission, primarily due to traffic congestion at these nodes. This phenomenon is evaluated using the packet loss probability, which is calculated by dividing the number of packets not received at the sink by the total number of packets sent from the source, as shown in equation (i).

$$\text{Packet loss rate} = (Tx - Rx) / Tx * 100\% \dots\dots\dots (1)$$

where Tx is the total number of packets transmitted, and Rx is the total number of packets received.

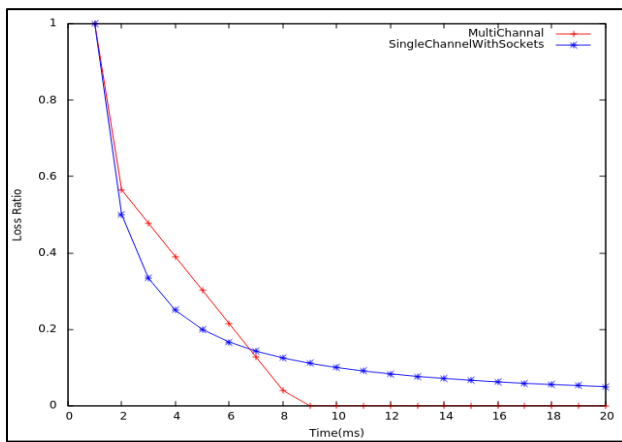


Fig 8a. Packet loss comparison of video, voice, and data under multichannel vs. single-channel multi-socket models (20 runs). Video loss is lowest, data highest.

4.2. Throughput

Throughput is defined as the number of packets successfully received at the sink node per unit time. The throughput is calculated using equation (ii).

$$\text{Throughput} = (Rx * 8.0 / (\text{time of LastRxPacket} - \text{time of FirstTxPacket}) / 1024) / 1024 \dots\dots\dots (ii)$$

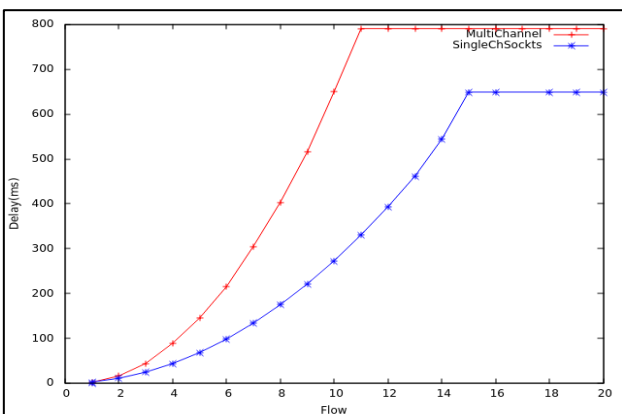


Fig 8b. Throughput comparison. Video achieves ~9.45 Mbps, voice 4.69 Mbps, data 3.71 Mbps. Results averaged over 20 runs.

4.3 Packet delay

Packet delay is defined as the time interval between when a packet is sent and when it is received by the destination node. Queueing delay at the receiver's end is also considered in the analysis. Packet delay is calculated using the formula given in equation (iii).

$$\text{Delay} = RTx - STx \dots\dots\dots (iii)$$

where RTx is the receiving time and STx is the sending time of the packet.

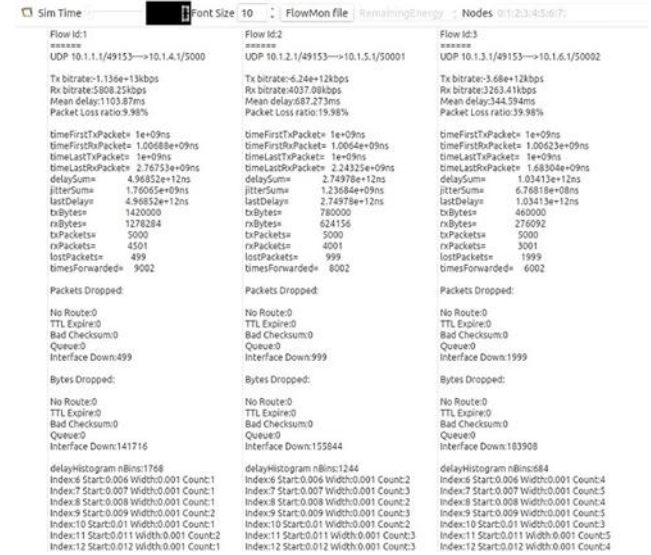


Fig 8c. Packet delay comparison. Single-channel multi-socket model shows lower average delays for video and voice.

4.4 Performance comparison for the single-channel multiple sockets proposed scheme.

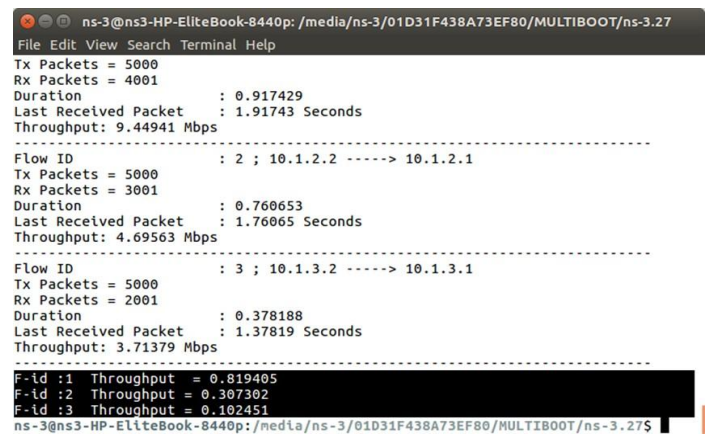
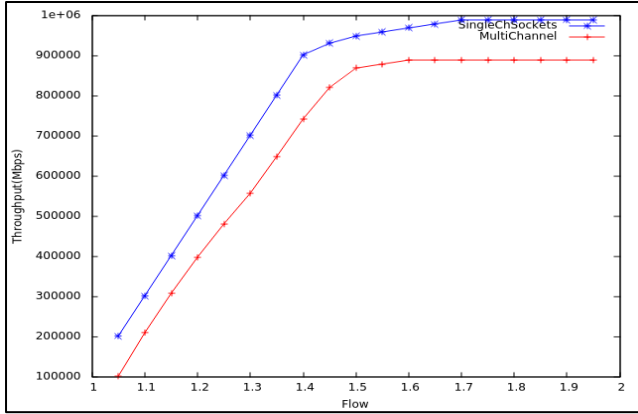


Fig 9. NetAnim output of the proposed single-channel multi-socket scheme. Video flows show higher rates and lower losses compared to voice and data.

The XML file was generated using the NetAnim tool and is shown in Fig. 9. Three types of packets are sent from the Base nodes to the Sink nodes: bursty packets (flow ID-1), voice packets (flow ID-2), and data packets (flow ID-3). It is evident that the rate of video packets is higher than that of data and voice packets, and video packet loss is lower in comparison to the other two types. The implementation of the proposed priority scheme resulted in noticeable performance improvement and more effective resource utilization.

For bursty traffic, the packet loss observed is 499 for video, 999 for voice, and 1,999 for data traffic. This corresponds to a loss of 9.98% for video, 19.98% for voice, and 39.98% for data packets. The measured throughput is 9.45 Mbps for video packets, 4.69 Mbps for voice packets, and 3.71 Mbps for data packets. These results show that the average throughput of video packets is higher than that of voice and data packets, indicating that the multi-socket model effectively improves throughput for video traffic.

Fig 10. Throughput distribution of video, voice, and data



packets. Video dominates due to socket-level prioritization.

5. Discussion

In this paper, we have presented a single-channel multi-socket wireless sensor network (WSN) model that incorporates socket-based traffic prioritization for video, voice, and data packets. By assigning priorities to different packet types, the model ensures that delay-sensitive traffic, particularly video and voice, is transmitted with minimal latency and reduced contention. Comparative performance evaluation with a multi-channel priority model demonstrates that the proposed single-channel approach significantly outperforms conventional multi-channel models in terms of end-to-end delay, throughput, and packet loss. These findings validate the effectiveness of the prioritization mechanism in optimizing network resource allocation within constrained WSN environments. The results suggest that, when managed intelligently, single-channel architectures can provide a cost-effective and efficient alternative to more complex multi-channel systems, especially in scenarios with diverse traffic requirements. Although packet loss, as shown in Fig. 8a, is higher than in the multi-channel priority model, the single-channel multi-socket approach achieves higher throughput and significantly lower delay, as illustrated in Figs. 8b and 8c. Further enhancements in QoS can be explored to reduce packet loss in the proposed model.

5. Conclusion

Users demand improved Quality of Service (QoS), while vendors seek optimal resource utilization. This

dual demand has presented significant challenges for researchers, who must devise methodologies that both optimize resource use and enhance QoS. In this research, we explore various priority schemes for handling high data rates where packet arrivals and departures occur in bursts. Our findings indicate that assigning dedicated sockets to video and voice packets can significantly improve network QoS. Additionally, adjusting the number of dedicated and shared channels or sockets allows for more efficient resource utilization.

Wireless sensor networks have evolved from scalar networks to multimedia wireless sensor networks (WSNs), enabling the retrieval of video, audio, and images alongside traditional scalar data. Recent advancements in sensor network technology have broadened their applications, resulting in widespread deployment to meet diverse user needs.

To address the challenges of heterogeneous and bursty traffic, we have designed a priority-based multi-socket single-channel WSN model. This model efficiently manages video, voice, and data traffic under heavy-tailed load conditions. Unlike conventional multi-channel systems, our approach uses socket-based prioritization to optimize channel access and favor latency-sensitive traffic. Simulation results demonstrate that the proposed model achieves significant performance improvements over multi-channel architectures, particularly in reducing end-to-end delays and increasing throughput across all traffic types. The model's ability to maintain robust performance under heavy-tailed, bursty traffic highlights the resilience and adaptability of the single-channel prioritization approach. These findings suggest that, with intelligent traffic classification and scheduling, single-channel WSNs can effectively support QoS-sensitive applications even in complex, unpredictable traffic environments.

6. Future Work

Future work will concentrate on integrating reinforcement learning-based scheduling into the single-channel WSN model to achieve adaptive and context-aware traffic management. By leveraging DQN, the system can dynamically adjust to bursty traffic patterns, optimize resource allocation, and ensure resilience beyond static priority schemes. This approach will be further validated through large-scale simulations to demonstrate improvements in QoS and scalability under practical 6G network conditions.

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