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Design and Performance Analysis of a Wireless CCTV Surveillance Network for Rural Road Safety: A Case Study in Alrujban City, Libya

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Abstract

The growing use of video surveillance systems requires reliable communication networks capable of supporting high-quality real-time streaming. This study evaluates the performance of a wireless network designed for CCTV transmission using the NS-3 simulation platform. The proposed network follows a star topology and consists of four communication links with different distances and bandwidth capacities to examine their behavior under varying traffic loads. This work is part of a broader research effort aimed at designing an efficient communication network to support road safety monitoring and traffic surveillance in mountainous urban environments. It also seeks to provide technical insights that may assist local authorities in developing reliable monitoring infrastructures and improving traffic management. The evaluation focuses on key Quality of Service (QoS) metrics, including throughput, delay, jitter, and packet loss. The results show that higher-capacity links maintain stable throughput and low delay under increased traffic load, while longer-distance links begin to experience congestion as the offered traffic approaches their capacity limits.

These findings highlight the importance of link capacity in network performance and confirm that a properly designed star-based wireless infrastructure can effectively support traffic surveillance systems in geographically challenging environments.

Keywords: Design and Performance- Analysis - Wireless CCTV - Surveillance Network - Rural Road Safety.

ملخص

يشهد استخدام أنظمة المراقبة بالفيديو تزايدًا ملحوظًا، مما يتطلب شبكات اتصال موثوقة قادرة على دعم البث المباشر عالي الجودة في الزمن الحقيقي. تهدف هذه الدراسة إلى تقييم أداء شبكة لاسلكية مخصصة لنقل بيانات كاميرات المراقبة (CCTV)باستخدام منصة المحاكاة NS-3 تعتمد الشبكة المقترحة على بنية نجمية (Star Topology) وتتكون من أربع وصلات اتصال تختلف في المسافات وسعات النطاق الترددي، وذلك لدراسة سلوكها تحت مستويات مختلفة من أحمال الشبكة. تندرج هذه الدراسة ضمن إطار بحثي أوسع يهدف إلى تصميم شبكة اتصالات فعّالة لدعم أنظمة مراقبة سلامة الطرق ومتابعة حركة المرور في البيئات الحضرية الجبلية، إضافة إلى تقديم مؤشرات تقنية يمكن أن تساعد السلطات المحلية في تطوير بنى تحتية موثوقة لأنظمة المراقبة وتحسين إدارة حركة المرور. تركز عملية التقييم على مؤشرات جودة الخدمة (QoS) مثل معدل النقل(Throughput) ، والتأخير(Delay) ، والتذبذب الزمني(Jitter) ، وفقدان الحزم (Packet Loss).وقد أظهرت النتائج أن الوصلات ذات السعة الأعلى تحافظ على أداء مستقر وتأخير منخفض حتى مع زيادة الحمل، بينما تبدأ الوصلات الأطول مسافة بإظهار تأثيرات الازدحام عند اقتراب الحركة المرورية من حدود سعتها.

توضح هذه النتائج أهمية سعة الرابط في أداء الشبكة، كما تشير إلى أن البنية اللاسلكية القائمة على التوصيل النجمي يمكن أن توفر حلاً موثوقًا لدعم تطبيقات مراقبة حركة المرور في البيئات الجغرافية الصعبة مثل المدن الجبلية.

1. Introduction

The growing population and lack of public transportation in Libya have led to a heavy reliance on cars. The country's vast geographic area necessitates a large road network to connect cities and regions. However, the current network, constructed during the 1980s and 1990s, is in a dilapidated state due to a lack of maintenance, particularly over the past decade of political instability. Excessive speeding by drivers, coupled with dilapidated roads and the very limited presence of traffic police staff at road crossings and highways to enforce speed regulations, contribute to a plague of serious traffic accidents, resulting in daily loss of life.

The motivation for the research and analysis conducted in this paper is the high mortality rate among the population in Libya in general and in the Hinterland in particular due to traffic accidents. Most of the fatalities are due to the delay in reporting accidents, which is often done by road users at the appropriate time, especially accidents that occur at isolated areas and intersections at times of low traffic.

According to official statistics published by the Ministry of Interior on November 9, 2023, for traffic accidents during the past five years (2018-2022), the number of deaths was 9245, with 11532 serious injuries, while the number of damaged vehicles during the mentioned period reached 39618 vehicles with an estimated value of 218 million Libyan dinars [1].

A video surveillance system refers to the practice of observing activities in public or private areas through cameras. Historically, a basic video surveillance system’s role was to capture footage using one or several cameras, then transmit the signal for display on a monitor and/or storage at a central site. Presently, advancements in video surveillance technology have facilitated the automated analysis of captured data Many studies carried out to find a solution to this issue, in this study a Closed-circuit television, or CCTV is used to monitor and determine the road users who has an excessive speed. CCTV is one of the most popular physical security systems. A security camera is a type of video collection equipment that is placed in a specific area and has multiple uses. With the recent improvements in CCTV capability, equipment is being created that tries to use facial recognition software to automate processing utilizing CCTV system-acquired facial data

2. Literature and Related Work

In the last decades, many researchers and developers have developed methods for monitoring roads to detect vehicles accidents and help monitoring traffic all over the highways roads and main crossroads, the techniques that used to achieve this purpose varied from the use of motion sensors, closed video circuits (CCTV) and image analysis using algorithms.

[1] presents an innovative method for detecting traffic congestion using image classification on CCTV camera feeds. It leverages a Convolutional Neural Network (CNN), which is a state-of-the-art image processing technique, requiring minimal preprocessing of small images. This approach contrasts with traditional methods that need high-quality images and manual feature extraction. The CNN model is trained to perform binary classification of road traffic conditions using a dataset of 1000 evenly distributed CCTV images. The study’s results show that the straightforward CNN architecture can achieve an average classification accuracy of 89.50% on grayscale images, demonstrating its effectiveness in traffic congestion detection.

A technique to transport video streams from cameras to external road traffic monitoring servers was proposed by [3] using smart live video adaptive streaming validation with several performance metrics in terms of Quality of Service and video quality.

(Zhang *et al.*, 2015) [4]research paper discusses Vigil, a wireless surveillance system that uses edge computing to analyze video data directly at the cameras. This reduces the amount of data transmitted wirelessly, saving bandwidth for other uses and allowing for much larger areas to be monitored compared to traditional systems.

Another study conducted by [5] explores how to improve CCTV placement in Smart Cities. Using cameras with the right technology and positioning them effectively is crucial for good monitoring. The study tested different camera types in various locations and achieved an accuracy of nearly 88% in predicting optimal placement with a Decision Tree model.

(Ukani *et al.*, 2017)[6] propose a system for real-time vehicle detection and classification in video surveillance, even with challenges like moving backgrounds and changing light and it achieves this by first separating vehicles from the background, then extracting unique features from each vehicle, it uses a Support Vector Machine to classify the vehicles making it useful for tasks like traffic monitoring and analysis.

The method proposed by [7]is almost uses similar methodology to the one used in this research they use an HD (High Definition) camera mounted on the road side either on a pole or on a traffic signal for recording video frames. On the basis of these frames, a vehicle can be tracked by using radius growing method, and its speed can be calculated by calculating vehicle mask and its displacement in consecutive frames.

3. Methodology of Proposed System

This study adopts a quantitative simulation-based feasibility methodology to evaluate the design and operational performance of a wireless CCTV surveillance network intended to enhance road safety in rural areas of Alrujban, Libya.

The objective of the methodology is to assess whether a wireless backbone infrastructure based on IEEE 802.11ac technology can reliably support real-time video transmission from distributed roadside cameras to a centralized control center under varying traffic conditions.

The methodological framework consists of four main phases:

1- Site selection and geographical analysis.
2- Radio link feasibility evaluation using radio mobile software.
3- Network simulation and QoS performance assessment using network simulator NS3.
4- Camera system configuration and deployment modeling using NS3.

In area study and Site Selection the study focuses on the city of Alrujban and its surrounding rural road network. Surveillance sites were selected based on the traffic density observations to capture patterns of congestion, road geometry analysis focusing on intersections and high-speed segments that may influence driver behavior, historical accident likelihood assessments to identify areas of elevated risk based on past incidents, and strategic coverage considerations to ensure that monitoring and resource allocation are distributed in a manner that maximizes both safety and operational effectiveness, four locations were identified for CCTV deployment, connected to a central control room located at the main police station in the city center.

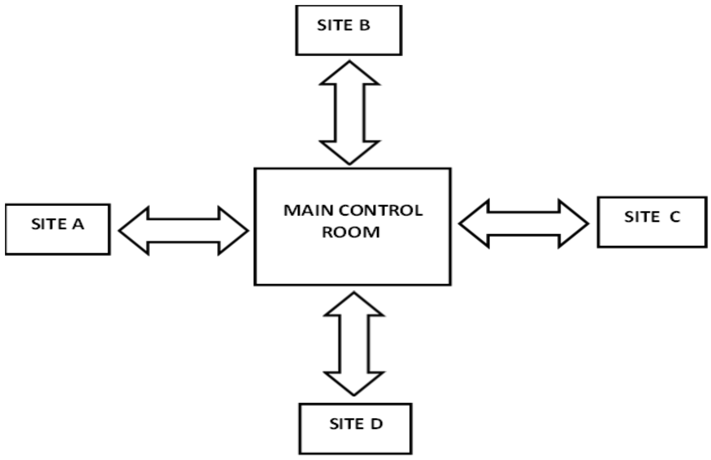


Figure 3.1 Proposed Star Topology of the CCTV Surveillance Network

Before network simulation, radio link viability between each surveillance site and the main control tower was evaluated using terrain profile analysis.

The following parameters were considered: ground elevation, antenna height, transmission power, free-space path loss, obstruction and diffraction losses and fade margin.

Radio link studies were performed to verify line-of-sight conditions and Fresnel zone clearance. Only links satisfying acceptable fade margin thresholds were considered viable for deployment.

Regarding wireless network simulation the wireless backbone network was modeled using the ns-3 network simulator and a star topology was implemented, where each remote surveillance site connects directly to the main control node. We use Frequency Band 5 GHz and WIFI standard IEEE 802.11ac.

Traffic modeling video traffic was modeled using UDP-based constant bit rate flows to emulate real-time CCTV streaming.
Offered load was varied incrementally from low to high rates (20Mbps 25Mbps ,30Mbps, 35Mbps ,40Mbps, 45Mbps) in order to evaluate network stability and congestion behavior. QoS Performance Evaluation includes the
The following Quality of Service (QoS) metrics were measured: Throughput (Mbps), Packet Loss Ratio (%), Average End-to-End Delay (ms) and Jitter (ms) For each load scenario, performance metrics were recorded and analyzed to determine the maximum stable throughput, saturation threshold, link degradation behavior and comparative performance among links.

The proposed system can be regarded as feasible when several critical performance criteria are satisfied, namely that packet loss remains within acceptable limits for real-time streaming, end-to-end delay stays below critical thresholds required for real-time communication, jitter does not undermine video stability, and wireless links consistently maintain adequate performance under the anticipated traffic load. Together, these conditions ensure the system’s reliability and effectiveness in supporting real-time applications.

4. Implementation

The proposed intelligent traffic monitoring system was implemented for the city of Alrujban, Libya. The network architecture is based on a centralized star topology, where a main aggregation node (MAIN_TOWER) is deployed near the city center, representing the police traffic control room server.

Four remote monitoring sites (SITE_A, SITE_B, SITE_C, and SITE_D) were selected along major roads and high-traffic areas, site selection was based on traffic density statistics, accident-prone locations, terrain elevation characteristics and Line-of-sight feasibility. Each site represents a CCTV camera tower transmitting real-time video streams to the central control server.

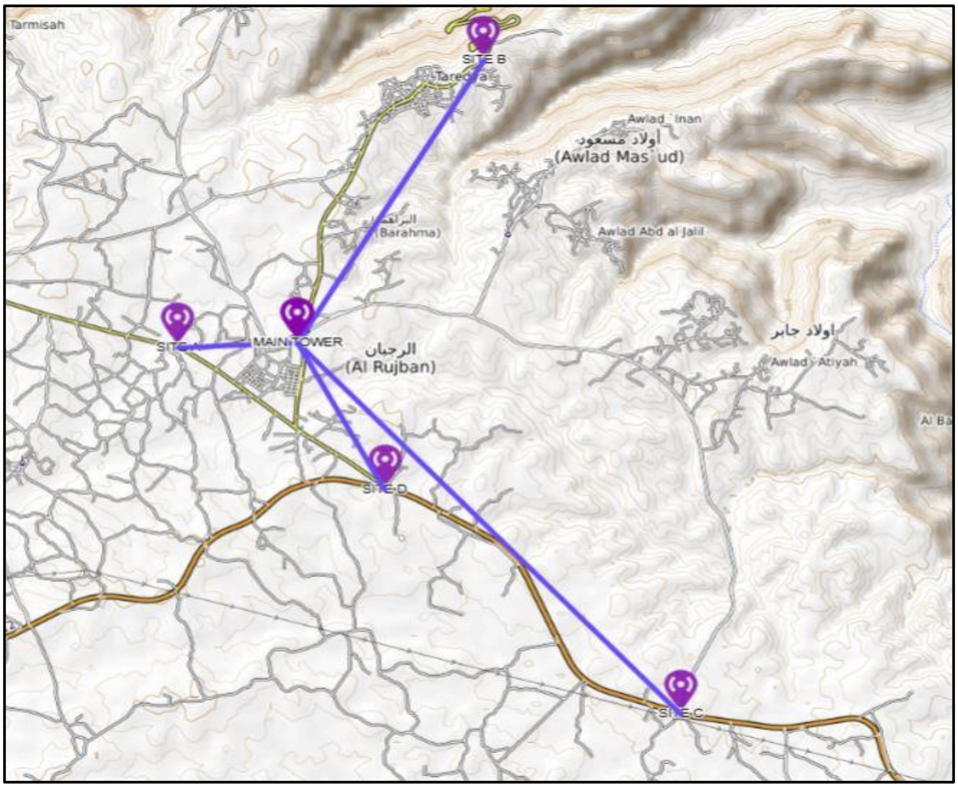
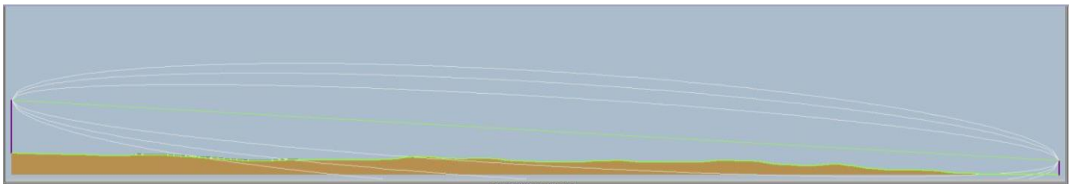


Figure 4.1 Geographical layout of the proposed star-based wireless CCTV network

4.1 Radio link line-of-sight analysis

Before network simulation, radio link feasibility was validated using Radio Mobile software. Terrain-based path profiles were analyzed to verify Line-of-sight (LoS) availability indicates how often the direct path between transmitter and receiver is unobstructed. Fresnel zone clearance specifies whether the first Fresnel zone is sufficiently free of obstacles to avoid significant diffraction losses. Obstruction loss represents the extra attenuation caused by terrain, buildings, or vegetation blocking the path or Fresnel zone. Total path loss is the overall attenuation along the link, combining free-space loss with all additional losses. Fade margin is the power headroom between the expected received level and the receiver threshold to ensure reliable operation under fading.

4.1.1 Link A analysis



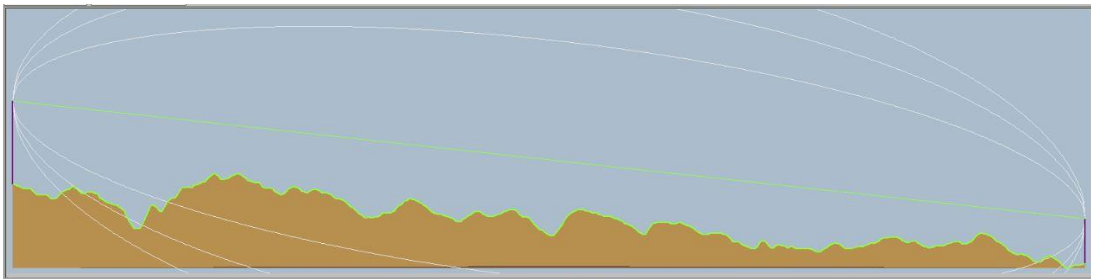
Radio link study 1			
MAIN TOWER (1)			(2) SITE A
Latitude	31.946284 °	Latitude	31.945573 °
Longitude	12.092391 °	Longitude	12.074616 °
Ground elevation	696.6 m	Ground elevation	678.3 m
Antenna height	45.0 m	Antenna height	12.0 m
Azimuth	267.31 TN | 264.66 MG °	Azimuth	87.30 TN | 84.65 MG °
Tilt	-1.76 °	Tilt	1.74 °
Radio system			**Propagation**
TX power	43.01 dBm	Free space loss	80.19 dB
TX line loss	3.00 dB	Obstruction loss	1.07 dB
TX antenna gain	6.00 dBi	Forest loss	0.00 dB
RX antenna gain	2.00 dBi	Urban loss	0.00 dB
RX line loss	0.50 dB	Statistical loss	5.12 dB
RX sensitivity	-113.02 dBm	Total path loss	86.38 dB

Performance	
Distance	**1.679 km**
Precision	10.0 m
Frequency	146.000 MHz
Equivalent Isotropically Radiated Power	39.905 W
System gain	160.53 dB
Required reliability	70.000 %
Received Signal	-38.87 dBm
Received Signal	2550.17 µV
Fade Margin	**74.15 dB**

Figure 4.2 Path profile and Fresnel zone analysis for Link A

Distance: 1.679 km
Total Path Loss: 86.38 dB
Fade Margin: 74.15 dB
The link exhibits excellent Fresnel clearance and high reliability margin.

4.1.2 Link C analysis



Radio link study 1**			
MAIN TOWER (1)			(2) SITE C
Latitude	31.946284 °	Latitude	31.891012 °
Longitude	12.092391 °	Longitude	12.149402 °
Ground elevation	696.6 m	Ground elevation	654.1 m
Antenna height	45.0 m	Antenna height	24.0 m
Azimuth	138.78 TN | 136.13 MG °	Azimuth	318.81 TN | 316.16 MG °
Tilt	-0.48 °	Tilt	0.41 °
Radio system			**Propagation**
TX power	43.01 dBm	Free space loss	93.93 dB
TX line loss	3.00 dB	Obstruction loss	5.17 dB
TX antenna gain	6.00 dBi	Forest loss	0.00 dB
RX antenna gain	2.00 dBi	Urban loss	0.00 dB
RX line loss	0.50 dB	Statistical loss	5.67 dB
RX sensitivity	-113.02 dBm	Total path loss	104.77 dB

Performance	
Distance	**8.169 km**
Precision	10.0 m
Frequency	146.000 MHz
Equivalent Isotropically Radiated Power	39.905 W
System gain	160.53 dB
Required reliability	70.000 %
Received Signal	-57.26 dBm
Received Signal	306.92 µV
Fade Margin	**55.76 dB**

Figure 4.3 Path profile and Fresnel zone analysis for Link C

Distance: 8.169 km
Total Path Loss: 104.77 dB
Fade Margin: 55.76 dB
Although this link has the highest distance and path loss, the fade margin remains acceptable for stable operation.

4.1.3 Radio Feasibility Summary

All four links achieved adequate Fresnel clearance and fade margins greater than 50 dB, confirming physical-layer feasibility before QoS evaluation.

4.2 Network Simulation Using NS-3

After validating the physical layer, the system was implemented in the NS-3 network simulator using C++ to evaluate Quality of Service (QoS) performance. The QoS metrics measured included throughput (Mbps), packet loss (%), average delay (ms), and jitter (ms). The simulation topology configuration is illustrated in Figure 6 (star architecture).

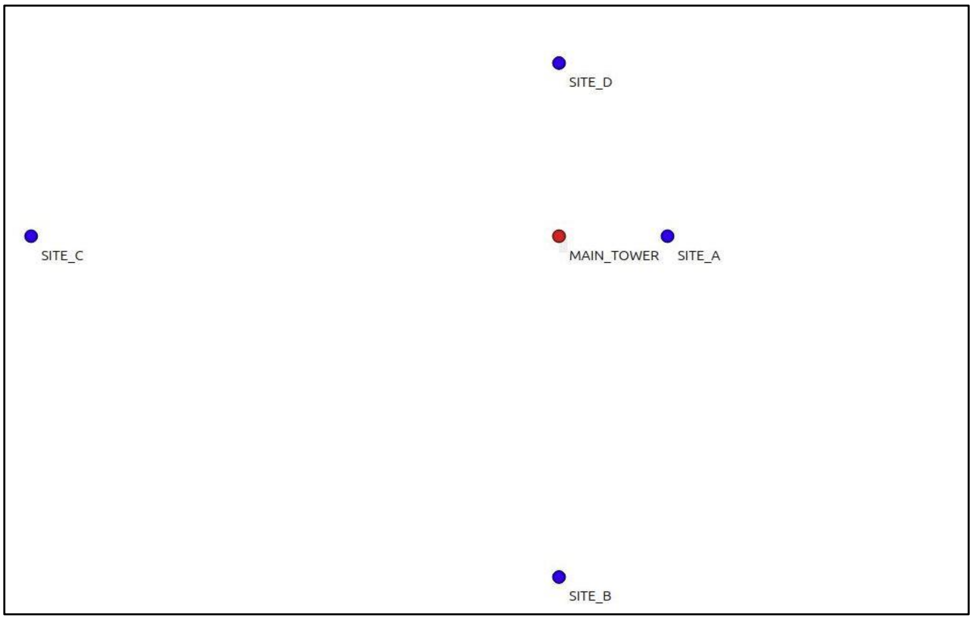


Figure 4.4 NS-3 NetAnim Visualization of the Proposed Star Topology

4.2.1 Simulation Parameters

Topology	Star
Wireless Standard	IEEE 802.11ac
Traffic Type	UDP Constant Bit Rate (CBR)
Simulation Duration	20 seconds
Tested Application Rates	20 – 45 Mbps

Table 4.1 Simulation Parameters

4.2.2 Links Parameters Analysis

The following link parameters were extracted from the Radio Mobile analysis for the mountainous area of Alrujban. Distances were determined based on terrain inspection and line-of-sight (LOS) assessment. The data rates were selected according to the predicted received signal strength in Radio Mobile. In addition, the clutter Loss Factor term (in milliseconds) was used to represent additional effects caused by mountainous terrain and vegetation cover.

```
std::vector<LinkParams> links = {
{"A", 1.679, "60Mbps", 0.8, 5001, "10.1.1.0", 0.85, 0.3},
{"B", 5.351, "40Mbps", 1.0, 5002, "10.1.2.0", 0.85, 1.2},
{"C", 8.169, "25Mbps", 1.2, 5003, "10.1.3.0", 0.85, 2.5),
{"D", 2.718, "50Mbps", 0.9, 5004, "10.1.4.0", 0.85, 0.8]
};
```

4.2.3 Target Transmission Rate Calculation with Safety Margin

To ensure realistic evaluation of the proposed surveillance system, a safety margin was applied to the baseline video transmission rate. This headroom accounts for potential network overhead, traffic fluctuations, and real deployment uncertainties. The following code segment calculates the effective offered load based on the selected base rate and the predefined headroom factor.

```
double baseRateMbps = 30.0;
if (baseRate == "25Mbps") baseRateMbps = 25.0;
else if (baseRate == "30Mbps") baseRateMbps = 30.0;
else if (baseRate == "35Mbps") baseRateMbps = 35.0;
else if (baseRate == "40Mbps") baseRateMbps = 40.0;
double offeredLoadMbps = baseRateMbps (1.0+ headroom Factor);
std::string targetAppRate = std::to_string((int) offered LoadMbps) +
"Mbps";
```

4.2.4 Offered Traffic Load Scenarios

To evaluate the sensitivity of the proposed surveillance network under varying traffic conditions, multiple application data rates were defined. These rates represent different video streaming scenarios, ranging from moderate load to saturation levels. This approach allows performance analysis under both normal and congested network conditions.

```
std::vector<std::string> appRates = {
  "20Mbps",
  "25Mbps",
  "30Mbps",
  "35Mbps",
  "40Mbps",
  "45Mbps"
};
```

4.2.5 Continuous Video Traffic Configuration

To simulate real-time CCTV video transmission, a continuous UDP traffic generator was implemented using the OnOff application model. The ON period was configured as constant (no OFF time) to emulate uninterrupted video streaming from each remote site toward the main control tower. The packet size and application rate were configured according to the evaluated network load scenarios.

```
OnOffHelper videoSource("ns3:: UdpSocketFactory",
                    InetSocketAddress (towerAddresses [i], L.port));
videoSource.SetAttribute("DataRate", StringValue(appRate));
videoSource.SetAttribute("PacketSize", UintegerValue (1400));
videoSource.SetAttribute("OnTime",StringValue("ns3::ConstantRandomVariabl
e [Constant=1]"));
videoSource.SetAttribute("OffTime", StringValue("ns3:: ConstantRandom
Variable [Constant=0]"));
ApplicationContainer srcApp videoSource. Install (nodes.Get(i + 1));
srcApp.Start(Seconds(startTime));
srcApp.Stop(Seconds (stopTime));
```

4.2.6 QoS Result Data Structure

To systematically store the performance metrics obtained from each simulated link, a structured data container was defined.The structure records the applied transmission rate, link identifier, and the main Quality of Service (QoS) metrics including throughput, packet loss, delay, and jitter. Additionally, a logical flag is used to confirm successful flow detection during simulation analysis.

```
struct LinkResult
{
std::string appRate;
std::string link;
double throughputMbps = 0.0;
```

```
double lossPct = 0.0;
double avgDelayMs = 0.0;
double avgJitterMs = 0.0;
bool flow Found = false;};
```

5. Performance Analysis

This section evaluates the performance of the proposed wireless surveillance network under different traffic loads. The Quality of Service (QoS) parameters were measured using the NS-3 simulation environment, based on the topology and link characteristics extracted from Radio Mobile analysis.

The analysis was conducted for different application data rates ranging from 20 Mbps to 45 Mbps in order to investigate the stability and reliability of each wireless link under increasing traffic demand.

The objective is to determine the operational capacity limits of each link and assess whether the network can support real-time 4K video streaming for traffic surveillance applications Table 5.1 summarizes the measured performance metrics before analytical interpretation.

app_rate mbps	link	distance km	Capacity mbps	throughput mbps	loss_pct	delay ms	jitter ms
20	A	1.679	60	20.4	0	1.191	0
20	B	5.351	40	20.4	0	2.286	0
20	C	8.169	25	20.4	0	3.458	0
20	D	2.718	50	20.4	0	1.229	0
25	A	1.679	60	25.5	0	1.191	0
25	B	5.351	40	25.5	0	2.286	0
25	C	8.169	25	25.102	1.561	122.703	0.016
25	D	2.718	50	25.5	0	1.229	0
30	A	1.679	60	30.6	0	1.191	0
30	B	5.351	40	30.6	0	2.286	0
30	C	8.169	25	25.102	17.968	138.52	0.129
30	D	2.718	50	30.6	0	1.229	0
35	A	1.679	60	35.7	0	1.191	0
35	B	5.351	40	35.7	0	2.286	0
35	C	8.169	25	25.102	29.686	139.334	0.157
35	D	2.718	50	35.7	0	1.229	0
40	A	1.679	60	40.8	0	1.191	0
40	B	5.351	40	40.08	1.763	80.975	0.011
40	C	8.169	25	25.102	38.476	139.633	0.131
40	D	2.718	50	40.8	0	1.229	0
45	A	1.679	60	45.9	0	1.191	0
45	B	5.351	40	40.081	12.677	86.834	0.062
45	C	8.169	25	25.102	45.311	139.792	0.069
45	D	2.718	50	45.9	0	1.229	0

Table 5.1 QoS Performance Results of the Proposed Surveillance Network

As shown in figure 5.1 the results for Link A demonstrate a linear relationship between the offered load and the achieved throughput. The throughput increases proportionally from 20 Mbps to 45 Mbps without any observable saturation or packet loss. This indicates that the link capacity (60 Mbps) is sufficient to accommodate the tested traffic loads, operating within a non-congested regime.

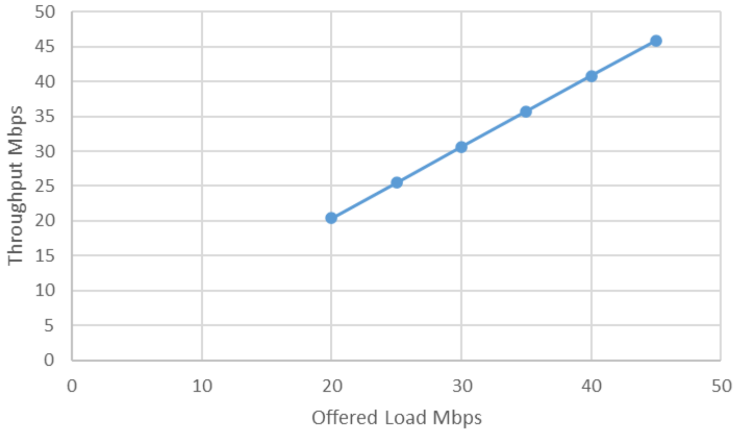


Figure 5.1 Throughput vs Offered Load for Link A

After confirming that Link A operates in a non-saturated region with linear throughput behavior and zero packet loss, further analysis is directed toward the longer-distance links (Link B and Link C).
Due to their greater propagation distances and lower link capacities, these links are more susceptible to congestion effects, increased latency, packet loss, and jitter under higher offered loads. Therefore, examining their performance provides a more realistic understanding of the network limitations under heavy traffic conditions.

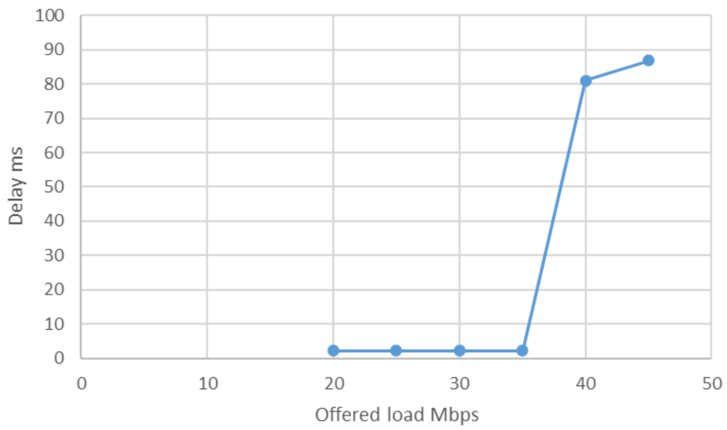


Figure 5.2 Delay vs Offered Load for Link B

The delay performance of Link B remains stable at low traffic loads (20–35 Mbps). However, a sharp increase in delay is observed once the offered load reaches 40 Mbps, indicating the onset of congestion. At 45 Mbps, delay remains significantly high, confirming that the link has reached its capacity limit and is operating under saturated conditions.

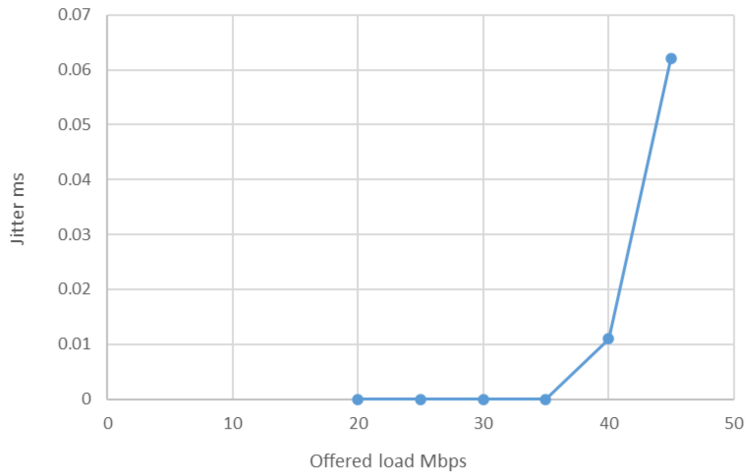


Figure 5.3 Jitter vs Offered Load for Link B

As it is clearly noticeable in figure 5.3 jitter performance of Link B remains negligible at lower traffic loads (20 –35 Mbps), indicating stable packet transmission with minimal delay variation. However, as the offered load approaches the link capacity (40 Mbps), jitter begins to increase.

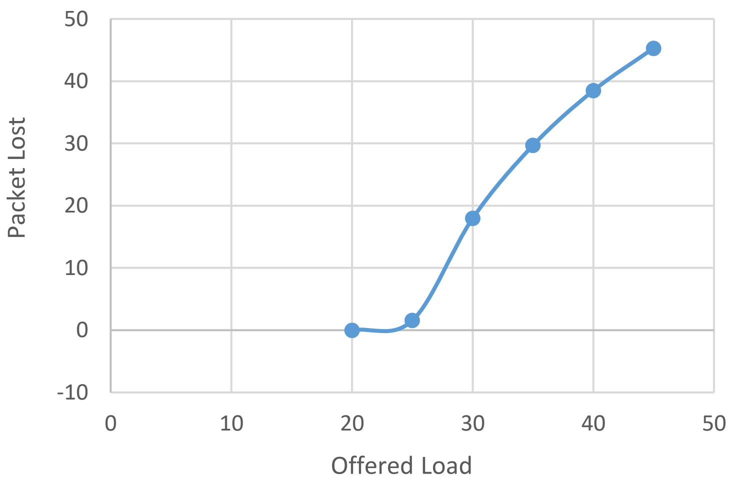


Figure 5.4 Packet lost vs Offered Load for Link C

The packet loss behavior of Link C shown in figure 5.4 clearly indicates early saturation. While the link performs reliably at 20 Mbps, packet loss begins to appear as the offered load approaches the nominal link capacity (25 Mbps).

Beyond this threshold, packet loss increases significantly, reaching approximately 45% at 45 Mbps. This confirms that Link C operates as the primary bottleneck in the network under high traffic conditions[8]

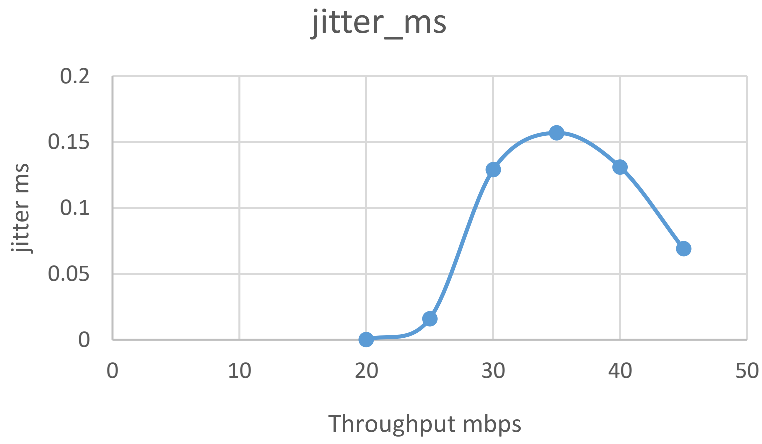


Figure 5.5 Jitter vs Offered Load for Link C

The jitter performance of Link C shown in figure 5.5 confirms early congestion behavior. While jitter remains negligible at 20 Mbps, it begins to increase as the offered load approaches the nominal link capacity (25 Mbps).

A sharp rise is observed between 30 and 35 Mbps, indicating significant queue buildup and delay variation. At higher loads (40–45 Mbps), jitter slightly decreases due to high packet loss, where only successfully transmitted packets are considered in the calculation. These results further validate that Link C is the primary bottleneck under heavy traffic condition[9].

Overall, the comparison confirms that short-range/high-capacity links (e.g., Link A) are well-suited for sustained 4K live streaming, whereas long-range/low-capacity links (especially Link C) require careful traffic engineering to maintain real-time surveillance requirement.

6. Limitations

Despite the promising results obtained from the simulation study, several limitations should be acknowledged.

First, the performance evaluation was conducted using NS-3 simulation rather than real-world deployment. Although realistic parameters derived from Radio Mobile were incorporated, actual field measurements may reveal additional environmental factors such as electromagnetic interference, equipment imperfections, and weather variability.

Second, the study assumes stable line-of-sight (LOS) conditions between the main tower and remote sites. In real mountainous terrain, seasonal vegetation growth, temporary obstacles, or structural changes could affect signal propagation and link reliability.

Third, the video traffic model was implemented using a continuous UDP On / Off application to emulate 4K streaming. While this approach approximates constant video transmission, it does not fully capture dynamic bitrate adaptation mechanisms such as H.264/H.265 variable bitrate encoding or real-time congestion control protocols.

Fourth, network security aspects such as encryption overhead, authentication latency, and cyber-attack resilience were not included in the current simulation model. In practical deployments, secure transmission mechanisms may introduce additional processing delays and bandwidth overhead.

Fifth, the proposed system focuses on a star topology with direct point-to-point links. Alternative architectures such as mesh or hybrid configurations were not evaluated and could provide different scalability and redundancy characteristics.

Finally, scalability analysis was limited to four remote sites. Expanding the network to a larger number of cameras may introduce congestion effects and routing complexities not captured in the current evaluation.

7. Future Directions

Future research may extend the current study in several directions:

First, real-world field measurements should be conducted in the Al-Rujban area to validate the simulation findings and compare practical performance against the NS-3 modeled results. This would provide empirical verification of propagation assumptions and QoS metrics.

Second, adaptive video encoding techniques such as H.265 variable bitrate streaming could be incorporated to evaluate the impact of dynamic traffic patterns on network stability. Implementing TCP-based streaming or congestion-aware protocols would further enhance realism.

Third, additional network architectures such as wireless mesh or hybrid topologies may be investigated to improve redundancy and fault tolerance in case of main tower failure.

Fourth, cybersecurity mechanisms including encryption (e.g., IPsec or TLS tunneling) could be integrated into the simulation framework to evaluate their impact on latency and throughput.

Fifth, scalability analysis with a larger number of remote camera sites should be performed to assess network expansion capabilities and backbone limitations.

Finally, integration with intelligent video analytics, such as AI-based vehicle detection and traffic density estimation, could transform the system from passive monitoring to proactive traffic management.

8. Conclusion

This study presented the design and simulation-based evaluation of a centralized wireless surveillance network for traffic monitoring in the mountainous area of Al-Rujban. The proposed system employs a star topology with dedicated point-to-point wireless links connecting multiple remote CCTV sites to a central control room. Radio Mobile was used to validate line-of-sight conditions and estimate link parameters, while NS-3 simulation was implemented to evaluate Quality of Service performance under varying traffic loads. The results demonstrated that links with higher capacity maintained stable throughput and low delay under increased load, whereas longer-distance links exhibited congestion effects as the offered traffic approached their capacity limits. The findings indicate that the proposed architecture is technically feasible for real-time 4K video transmission, provided that link capacities are carefully dimensioned according to terrain characteristics and expected traffic demand.

Overall, the study confirms that a properly engineered star-based wireless infrastructure can support reliable traffic surveillance in geographically challenging environments.

9. References

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