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Analytical Modelling of an Elevated-Tower Fibre-Optic Surveillance Platform: Coverage, Link Budget and Solar-Power Assessment

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ABSTRACT

This study presents the analytical modelling and performance evaluation of a low-altitude elevated-tower fibre-optic communication platform for security surveillance. The proposed platform integrates CCTV cameras, a thermal camera, AI-based motion detection, single-mode fibre-optic communication and a solar-powered energy system. System performance was evaluated at tower heights ranging from 10 m to 100 m. The modelled line-of-sight coverage radius increases from 11.29 km to 35.70 km, while the theoretical geometric coverage area expands from approximately 400 km² to 4,003 km². Camera ground viewing width increases from 11.55 m to 115.47 m, assuming a vertical field of view of 60° and a downward-facing camera. These coverage values represent theoretical geometric estimates rather than verified target-detection ranges. Estimated fibre attenuation ranges from 0.0035 dB to 0.035 dB for assumed fibre lengths of 10–100 m. The gross optical power budget is 28 dB, while the usable budget reduces to 23 dB after accounting for assumed component losses and an engineering margin, giving an adjusted theoretical maximum fibre distance of 65.71 km. Quantitative SNR and BER performance was not established because the required receiver and modulation parameters were not fully specified. The estimated average electrical load is 160 W, corresponding to a daily energy requirement of 3.84 kWh. A preliminary solar PV capacity of 1.2 kWp and battery capacity of approximately 10.1–15.2 kWh is proposed for 48–72 hours of autonomy. A tower height range of 60–70 m is identified as a candidate design option requiring further engineering validation.

INTRODUCTION

A low-altitude elevated-tower fibre-optic communication platform is a proposed surveillance infrastructure that combines elevated structures, optical telecommunications, electronic sensors, and intelligent monitoring technologies to support the collection and transmission of security-related data over extended geographical areas (Fidler et al., 2010; Keiser, 2021; Demirsoy et al., 2026). In telecommunications and security engineering, such a platform can use single-mode fibre-optic links to transmit data from surveillance devices, including high-definition cameras and sensors, to central monitoring facilities. Its potential performance depends on factors such as tower height, theoretical line-of-sight coverage, camera viewing geometry, optical link characteristics, and power availability (Freeman, 2007; Agrawal, 2012; Djordjevic, 2018; Kareem et al., 2021; Keiser, 2021; Boffi et al., 2022; Veeranna et al., 2023).

Security threats, including banditry, insurgency, kidnapping, bombings, and armed robbery, remain serious challenges in Nigeria, with consequences for public safety, economic activities, and national stability (George et al., 2020; Abdulrasheed, 2021; Mezie-Okoye, 2021; Udosen & Uwak, 2021; Okwuwada, 2023). Conventional security responses, including counter-insurgency operations and punitive measures, may be costly and may not independently provide continuous surveillance across extensive geographical areas (Sowale, 2025; Alli, 2026; Ogbozor, 2026). These challenges highlight the need for complementary technological solutions that support security personnel through improved monitoring, timely information transmission, and early identification of suspicious

activities (Cadet, 2024; Zada et al., 2026). Elevated surveillance towers supported by fibre-optic communication and reliable solar power could provide a useful approach for monitoring selected rural, urban, and other security-sensitive locations (Moepi et al., 2025; Sharma et al., 2026).

Previous research relevant to the proposed platform can be considered in relation to tower geometry and camera viewing coverage, fibre-optic communication, and off-grid solar power. Studies relating to elevated structures and surveillance geometry provide a basis for examining the relationship between mounting height, theoretical line-of-sight distance, and camera viewing footprints (Kassim et al., 2019; Suresh et al., 2020; Wu et al., 2024; Güneş et al., 2026). However, geometric visibility should be distinguished from effective camera detection, which also depends on camera resolution, lens characteristics, target size, camera orientation, and environmental conditions. Fibre-optic technology is also relevant to the proposed platform because of its low attenuation, high bandwidth, and immunity to electromagnetic interference. These properties support the transmission of high-definition video and sensor data between remote surveillance points and central monitoring facilities (Agrawal, 2012; Tejedor et al., 2017; Keiser, 2021; Veeranna et al., 2023; Liu et al., 2025). It is important to distinguish fibre-optic telecommunications, which uses optical fibre to transmit information, from fibre-optic sensing, which uses changes in optical signals to detect physical conditions such as temperature, strain, or vibration. Related research has also investigated the integration of distributed fibre-optic sensing, Internet of Things (IoT) devices, cameras and deep-learning algorithms for intelligent border surveillance and intrusion detection (Sharma et al., 2026). The present study considers single-mode fibre as a telecommunications medium for data transmission rather than as a distributed sensing system (Fidler et al., 2010; Hui & O'Sullivan, 2022; Elsherif et al., 2022; Udd, 2024). In addition, solar photovoltaic systems incorporating charge controllers and battery storage are relevant to remote surveillance installations because they can provide electrical power where grid supply is limited. Their suitability depends on equipment load, daily energy consumption, available solar irradiation, battery capacity, and the required backup period. Advances in spatial data analysis, geospatial mapping, machine learning, and computer vision have also expanded the potential for automated anomaly identification, risk assessment, and emergency response optimisation (Tejedor et al., 2017; Okolo et al., 2022; Rane et al., 2024; SAPEA, 2025).

Despite the relevance of these individual technologies, further integrated analytical investigation is needed to assess their combined requirements within an elevated-tower fibre-optic surveillance platform. In particular, the relationship between tower height and theoretical line-of-sight coverage, the corresponding camera viewing width, the optical link budget under practical transmission losses, and the energy requirements of a solar-powered surveillance system requires systematic evaluation. For this purpose, the present study considers tower heights ranging from 10 m to 100 m and evaluates the associated coverage radius, geometric coverage area, camera viewing width, fibre attenuation, optical power budget, and solar-power requirements. This integrated assessment provides a measurable basis for examining the technical feasibility and design considerations of the proposed platform without treating geometric visibility as verified target-detection performance.

The aim of this study is to develop an analytical model for evaluating the geometric coverage, camera viewing width, fibre-optic link performance, and solar-power requirements of a low-altitude elevated-tower surveillance platform over tower heights ranging from 10 m to 100 m. The model is intended to provide a technical basis for identifying a candidate tower height and system configuration for further engineering evaluation.

MATERIALS AND METHODS

This study employed an analytical modelling approach to design and evaluate a low-altitude elevated tower fibre-optic communication platform for security surveillance. The methodology focused on assessing the effects of tower height on theoretical line-of-sight coverage, geometric coverage area, camera ground viewing width and optical signal transmission. Mathematical models were used to estimate the key geometric and optical link parameters under defined design assumption. Solar-hybrid power supply is also incorporated to assess the energy requirements for continuous system operation.

System Architecture and Design

The proposed surveillance platform comprised three principal subsystems: surveillance, communication, and power supply. These subsystems were designed to operate as an integrated system for image acquisition, data transmission, and continuous monitoring.

Surveillance Subsystem

The surveillance subsystem consisted of 4K Internet Protocol (IP) closed-circuit television (CCTV) cameras, thermal imaging cameras, and artificial intelligence (AI)-based motion detection sensors. The 4K IP cameras were intended for daytime monitoring, while thermal cameras were incorporated to support surveillance at night and under low-visibility conditions. AI-based motion detection was included to facilitate the identification of movement and potentially suspicious activities.

A multi-camera configuration was adopted to provide 360° surveillance coverage around the tower. Edge processing was incorporated into the proposed architecture to enable preliminary data processing near the point of acquisition, thereby reducing the volume of data transmitted to the control room and potentially minimizing communication latency.

Communication Subsystem

The communication subsystem was designed around single-mode fibre-optic cable (SMF-28) to provide high-capacity data transmission between the surveillance platform and the control room. The proposed communication pathway consisted of the surveillance cameras, edge switch, optical transceiver, fibre-optic cable, and control-room receiving equipment. The communication architecture was represented as follows:

Cameras → Edge Switch → Optical Transceiver → Fibre-Optic Cable → Control Room

Single-mode fibre was selected because of its low attenuation, high bandwidth, and immunity to electromagnetic interference. These characteristics make it suitable for transmitting surveillance data over extended distances. The communication performance was evaluated using fibre attenuation, received optical power, signal-to-noise ratio (SNR), and estimated bit error rate (BER).

Power Subsystem

A solar-hybrid power configuration was incorporated into the proposed system to support continuous surveillance operation, particularly in locations with limited access to a reliable electricity supply. The power subsystem comprised a solar photovoltaic (PV) array, maximum power point tracking (MPPT) charge controller, lithium iron phosphate ($LiFePO_4$) battery bank, pure sine-wave inverter, and DC distribution unit. The system was designed to accommodate the electrical requirements of the surveillance cameras, communication equipment, and associated processing devices. A backup autonomy period of 48–72 hours were adopted as the design target to maintain operation during periods of inadequate solar energy generation. The required PV array and battery capacities were determined from the estimated daily energy consumption and the specified backup duration.

Design Assumptions and Parameters

The analytical evaluation was conducted using the parameters presented in Table 3.1. These parameters represented the principal geometric, optical, and communication characteristics used in the mathematical models.

Table 3.1: Design parameters and assumed values for system modelling

Parameter	Symbol	Value
Earth radius	R_e	6.371×10^6m
Camera vertical field of view	θ	60° (assumed)
Fibre attenuation coefficient	α	0.35 dB/km
Transmitter optical power	P_t	0 dBm
Receiver sensitivity	$P_{\min}$	−28 dBm
Assumed noise power	P_n	−90 dBm
Fibre type	—	Single-mode (SMF-28)
Tower height range	h	10–100 m
Target backup autonomy	T_b	48–72 hours
Assumed fibre route length	L	100 m (0.1 km)
Combined connector, splice and component losses	L_c	2.0 dB
Engineering link margin	M_{design}	3.0 dB

Notes

1. Earth radius: Expressed in metres (6.371×10^6 m), which give $d$in metres when $h$is expressed in metres.
2. Camera vertical field of view: Specified as vertical because Equation (5) uses the vertical viewing angle for a downward-facing camera. The 60° value is an assumption and should be checked against the camera manufacturer's datasheet.
3. Assumed fibre route length: Lrepresents the optical fibre route length, independent of tower height h. The 100 m value is the reference route length used for the system link-budget assessment, while the maximum attenuation-limited route length is calculated separately from the available optical power budget.
4. Assumed noise power: The −90 dBm value is a modelling assumption. Without a specified receiver noise model and measurement bandwidth, it cannot establish a validated signal-to-noise ratio (SNR).
5. Optical link-budget parameters: The combined connector, splice and component losses ($L_c = 2.0$ dB) and engineering link margin ($M_{\text{design}} = 3.0$ dB) are included in the link-budget calculation. Here, $P_t$and $P_{\min}$represent optical power levels in dBm,

while L_c, $M_{\text{design}}$and $L_{\text{fibre,max}}$represent losses or budgets in dB. The usable fibre-loss budget is calculated as:

$L_{\text{fibre,max}} = P_t - P_{\min} - L_c - M_{\text{design}} = 0 - (-28) - 2 - 3$

$L_{\text{fibre,max}} = 23$ dB

Using the assumed fibre attenuation coefficient of 0.35 dB/km, the corresponding attenuation-limited maximum fibre route length is:

$L_{\max} = \frac{L_{\text{fibre,max}}}{\alpha} = \frac{23 \text{ dB}}{0.35 \text{ dB/km}} L_{\max} = 65.71$ km

This value represents a theoretical link-budget limit under the stated assumptions.

Mathematical Modelling

Mathematical models were developed to evaluate the geometric coverage and optical communication performance of the proposed surveillance platform. Tower height was treated as the principal independent variable, while coverage radius, coverage area, camera viewing width, and relevant communication parameters were evaluated as dependent variables.

Line-of-Sight Coverage Model

The theoretical line-of-sight distance from the top of the surveillance tower to the Earth's horizon was estimated using the geometric relationship between tower height and the curvature of the Earth:

$$d = \sqrt{(R_e + h)^2 - {R_e}^2} \quad (1)$$

$$d \approx \sqrt{2R_e h} \quad (2)$$

where d is the theoretical line-of-sight distance (m), R_e is the Earth's radius (m), and h is the tower height above ground level (m). For consistency of units, $R_e = 6.371 \times 10^6$ m should be used when h is expressed in metres, in which case d is obtained in metres.

Coverage Area

The theoretical ground coverage area was estimated by assuming a circular surveillance region of radius d:

$$A = \pi d^2 \quad (3)$$

where A is the theoretical coverage area (m^2), d is the theoretical coverage radius (m), and π is a mathematical constant (≈ 3.14159). To express the coverage area in square kilometres:

$$A_{km^2} = \frac{\pi d^2}{10^6} \quad (4)$$

where d is expressed in metres. This model provides a simplified geometric estimate of the area potentially visible from the tower. It does not account for obstacles, overlapping camera views, blind spots, or the effective detection range of the surveillance equipment.

Camera Viewing Geometry

The ground viewing width of a vertically downward-facing camera was estimated from the camera's vertical field of view and the vertical distance between the camera and the target plane:

$$W = 2h \tan\left(\frac{\theta}{2}\right) \quad (5)$$

where $W$is the ground viewing width (m), $h$is the camera height above the ground (m), and $\theta$is the camera's vertical angular field of view (degrees). For the adopted field of view of 60°, the expression becomes:

$W = 2h\tan(30°) = 1.1547h$

The model assumes a level ground surface and a vertically downward-facing camera. The 60° value is treated as an assumed vertical field of view and should be checked against the camera's actual datasheet. In practical installations, camera tilt and mounting orientation may differ from the assumed vertical position, thereby affecting the ground footprint.

The calculation estimates geometric viewing width only. It does not determine whether a person, vehicle or other target can be detected or identified. Such an assessment would require the camera's focal length, sensor resolution, number of pixels projected across the target, target dimensions, camera tilt and mounting orientation, and environmental conditions. These parameters were not specified in the present study; therefore, no quantitative detection or identification range is claimed.

The horizon distance (Equations 1–2) and the camera viewing width (Equation 5) describe different geometries and cannot be combined to infer effective target detection at horizon distances. The geometric coverage values reported in this study therefore represent theoretical line-of-sight visibility and idealised ground footprints, not verified target-detection or identification ranges.

In Equation (5), $h$is the vertical distance from the camera to the ground plane. This distance equals the tower height only when the camera is mounted at the tower top and the ground plane is at the assumed reference elevation. If the camera is mounted below the tower top or the ground elevation varies, the actual camera height must be used.

Fibre Attenuation Model

The attenuation of the optical signal along the fibre-optic link was estimated using:

$$L_f = \alpha L \quad (6)$$

where L_f is the fibre attenuation (dB), α is the fibre attenuation coefficient (dB/km), and L is the fibre length (km). The model assumes uniform attenuation along the fibre and excludes additional losses from connectors, splices, bends, and other optical components.

Optical Link Power Model

The received optical power was estimated using the optical link power budget:

$$P_r = P_t - L_f - L_c \quad (7)$$

where P_r is the received optical power (dBm), P_t is the transmitter optical power (dBm), L_f is the fibre attenuation (dB), and L_c is the combined insertion loss from connectors, splices, and other optical components (dB). For a simplified link in which additional component losses are neglected, the model reduces to $P_r = P_t - \alpha L$.

The estimated received power was compared with the receiver sensitivity to determine whether the optical signal remained within the specified operating range. The optical link margin was calculated as:

$$M = P_r - P_{min} \quad (8)$$

where M is the link margin (dB) and P_{min} is the receiver sensitivity (dBm). A positive margin indicates that the estimated received power exceeds the minimum sensitivity threshold, although an adequate practical design must also allow for component tolerances, aging, and other system losses.

Signal-to-Noise Ratio

The signal-to-noise ratio was evaluated to describe the relationship between the received signal power and the associated noise power. When signal and noise powers are expressed in dBm over the same measurement bandwidth, the SNR in decibels is given by:

$$SNR_{dB} = P_s - P_n \quad (9)$$

where $\boldsymbol{P_s}$ is the received signal power (dBm) and $\boldsymbol{P_n}$ is the noise power (dBm). For a valid communication-system assessment, the noise power must correspond to the receiver bandwidth and operating conditions. The assumed noise level of −90 dBm was therefore treated as a modelling parameter rather than a measured receiver characteristic. Although Equation (9) is retained as the general relationship, the receiver bandwidth and noise model were not specified sufficiently to establish a validated quantitative SNR. Consequently, no quantitative SNR result is used to establish the communication performance of the proposed platform.

Bit Error Rate Estimation

The bit error rate (BER) was considered as an indicator of the reliability of the transmitted digital data. For an ideal binary phase-shift keying (BPSK) system operating in additive white Gaussian noise (AWGN), an illustrative theoretical expression is given by Proakis and Salehi (2008):

$$BER = Q\left(\sqrt{\frac{2E_b}{N_0}}\right) \quad (10)$$

where $E_b$is the energy per bit, $N_0$is the noise power spectral density, and $Q(\cdot)$is the Gaussian tail probability function. Equation (10) represents an ideal coherent BPSK/AWGN communication model and is not a validated BER model for the proposed optical communication link. Its application would require a specified optical modulation scheme, detection method, receiver characteristics and an appropriate relationship between SNR and BER. Since these parameters were not defined in the present study, no quantitative BER performance is claimed for the proposed platform.

Solar Power System Design Method

The solar-hybrid power subsystem was dimensioned using estimated electrical loads, assumed operating factors, and standard sizing equations. The design process comprised load estimation, daily energy calculation, PV array sizing, battery capacity determination, and a sensitivity analysis. The proposed surveillance and communication equipment operates directly from a 48 V DC bus; the battery-sizing calculation therefore uses Equation (14) without an inverter-efficiency term.

Load Estimation

The total connected load was calculated by summing the rated power of the connected equipment:

$$P_{total} = \sum_{i=1}^{n} P_i \quad (11)$$

where $P_{total}$is the total connected load (W), $P_i$is the rated power of the i-th device (W), and $n$is the number of connected devices.

Because equipment does not operate continuously at rated power, an average load factor was assigned to each category. The average operating power was estimated as:

$$P_{avg} = \sum_{i=1}^{n} P_i f_i$$

where f_i is the assumed average load factor.

Table 3.2: Electrical load estimates and assumed operating factors

Equipment	Quantity	Rated power per unit (W)	Load factor	Average power (W)
4K IP CCTV cameras	4	80	0.25	80
Thermal camera	1	25	0.40	10
Network switch and optical transceiver	1 set	40	1.00	40
AI processing unit	1	30	0.50	15
Sensors and electronics	1 set	15	1.00	15

Total	430	160

Calculations:

$P_{\text{total}} = 320 + 25 + 40 + 30 + 15 = 430$ W$P_{\text{avg}} = (320 \times 0.25) + (25 \times 0.40) + (40 \times 1.00) + (30 \times 0.50) + (15 \times 1.00) = 160$ W

The load factors and equipment power ratings are assumed design values used for preliminary modelling and should be verified against the manufacturers' datasheets or measured operating consumption before implementation.

Daily Energy Requirement

The daily energy requirement was calculated from the average operating power and operating duration:

$$E_{\text{daily}} = P_{\text{avg}} \times t \qquad (12)$$

where $E_{\text{daily}}$is the daily energy consumption (Wh/day), $P_{\text{avg}}$is the average load power (W), and $t$is the operating duration (h/day).

$E_{\text{daily}} = 160 \times 24 = 3{,}840$ Wh/day

Solar Photovoltaic Array Sizing

The required PV array capacity was estimated from the daily energy demand and the expected peak-sun-hour availability (Messenger & Abtahi, 2017):

$$P_{\text{PV}} = \frac{E_{\text{daily}}}{H_{\text{PSH}} \times \eta_{\text{sys}}} \qquad (13)$$

where $P_{\text{PV}}$is the required PV array capacity (W), $E_{\text{daily}}$is the daily energy requirement (Wh/day), $H_{\text{PSH}}$is the average daily peak-sun-hours (h/day), and $\eta_{\text{sys}}$is the overall system efficiency expressed as a decimal. The PV design inputs are summarised in Table 3.3.

Table 3.3: PV and battery design inputs

Parameter	Symbol	Assumed value
Daily energy requirement	E_{daily}	3,840 Wh/day
Peak sun hours	H_{PSH}	5 h/day (assumed)
Overall system efficiency	η_{sys}	0.75 (assumed; includes module temperature, dust, wiring, charge-controller and battery charging losses)
Nominal battery voltage	V_{bat}	48 V (assumed)
Allowable depth of discharge	DoD	0.80 (assumed)
Battery discharge efficiency	η_{bat}	0.95 (assumed)
Backup autonomy	t_b	48–72 h

The overall system efficiency $\eta_{\text{sys}} = 0.75$includes module temperature effects, dust and soiling, PV wiring losses, charge-controller losses and battery charging losses. No separate efficiency factor is applied for these losses, to avoid double-counting.

Worked calculation:

$$P_{\text{PV}} = \frac{3{,}840}{5 \times 0.75} = 1{,}024 \text{ W} \approx 1.02 \text{ kWp}$$

A preliminary nominal PV array capacity of 1.2 kWp is proposed. This is a preliminary analytical design estimate based on assumed inputs; it is not an experimentally validated or installed array rating.

Battery Capacity Sizing

The battery bank was designed to provide 48–72 hours of backup autonomy during periods of insufficient solar generation. The required nominal battery capacity was estimated using the standard sizing relation (Messenger & Abtahi, 2017):

$$C_{\text{Ah}} = \frac{P_{\text{avg}} \times t_b}{V_{\text{bat}} \times DoD \times \eta_{\text{bat}}} \qquad (14)$$

where $C_{\text{Ah}}$is the nominal battery capacity (Ah), $P_{\text{avg}}$is the average load power (W), $t_b$is the backup duration (h), $V_{\text{bat}}$is the nominal battery voltage (V), DoD is the allowable depth of discharge expressed as a decimal, and $\eta_{\text{bat}}$is the battery discharge efficiency.

Worked calculation for 48 hours autonomy:

$$C_{\text{Ah}} = \frac{160 \times 48}{48 \times 0.80 \times 0.95} = 210.53 \text{ Ah}$$

Worked calculation for 72 hours autonomy:

$$C_{\text{Ah}} = \frac{160 \times 72}{48 \times 0.80 \times 0.95} = 315.79 \text{ Ah}$$

The theoretical battery requirements are approximately 48 V, 211 Ah for 48 hours and 48 V, 316 Ah for 72 hours. These are preliminary analytical design estimates based on assumed inputs, not experimentally validated or installed battery capacities. The 48 V value is an assumed nominal system voltage; the selected $LiFePO_4$ battery bank may be rated at 51.2 V nominal, in which

case the capacity in Ah must be recalculated. The final battery bank should be selected from commercially available $LiFePO_4$ ratings, allowing for ageing, temperature and manufacturer limits.

Sensitivity analysis:

Table 3.4: PV capacity sensitivity to peak sun hours

Peak sun hours	Required PV capacity (W)
4	1,280
5	1,024 (baseline)
6	853

Table 3.5: Battery capacity sensitivity to backup duration

Backup duration (h)	Required capacity (Ah)
48	210.53
60	263.16
72	315.79

Table 3.6: Battery capacity sensitivity to allowable depth of discharge (72 h backup)

Allowable DoD	Required capacity (Ah)
0.70	361
0.80	316 (baseline)
0.90	281

The 0.90 DoD case should only be adopted if the selected battery manufacturer's specifications permit it.

The charge controller, cabling and protection devices must also be rated to accommodate the system's electrical load and operating requirements. These calculations provide a reproducible preliminary analytical design basis. They are not experimentally validated or installed equipment specifications. They become equipment-specific design inputs only after the equipment power ratings and operating profiles are verified against datasheets or measured consumption.

RESULTS AND DISCUSSION

Coverage Analysis

The theoretical geometric coverage was evaluated for tower heights ranging from 10 to 100 m at intervals of 10 m. The calculated coverage radii and corresponding coverage areas are presented in Table 4.1.

The results indicate that the theoretical line-of-sight coverage radius increases as tower height increases. The estimated radius rises from 11.29 km at a height of 10 m to 35.70 km at 100 m. Similarly, the corresponding theoretical geometric coverage area increases from approximately 400 km² to 4,003 km².

This trend is consistent with the geometric relationship between tower height and the Earth's curvature. Under the adopted model, the coverage radius increases approximately with the square root of tower height, while the theoretical coverage area increases approximately in proportion to tower height. Consequently, increasing tower height can substantially expand the geographical region within the theoretical line of sight.

However, these values represent idealized geometric coverage rather than verified camera detection or identification ranges. Actual surveillance performance depends on terrain, buildings, vegetation, camera resolution, lens characteristics, target size, and environmental conditions. Therefore, the calculated areas should be interpreted as theoretical geometric coverage estimates rather than guaranteed areas of effective security surveillance.

Table 4.1: Relationship between tower height and theoretical geometric coverage

Tower height (m)	Coverage radius (km)	Coverage area (km²)
10	11.29	400
20	15.96	801
30	19.55	1,201
40	22.58	1,601
50	25.24	2,002
60	27.65	2,402
70	29.87	2,802
80	31.93	3,202
90	33.86	3,603

100	35.70	4,003

Camera Viewing Results

The ground viewing width of the surveillance camera was evaluated at selected mounting heights, assumed to correspond to the tower heights, using a vertical field of view of 60° and a vertically downward-facing camera orientation. The results are presented in Table 4.2.

The results demonstrate a linear relationship between tower height and geometric ground viewing width under the assumed camera geometry. The viewing width increases from 11.55 m at a height of 10 m to 115.47 m at 100 m. This trend indicates that increasing the vertical distance between the camera and the ground expands the camera's ground footprint when the field of view remains constant.

The wider viewing footprint may support the monitoring of larger ground areas. However, an increase in viewing width does not necessarily guarantee improved target detection or identification. These capabilities also depend on image resolution, lens specifications, target characteristics, camera orientation, and image-processing performance. Therefore, the results demonstrate the geometric effect of tower height rather than a direct measurement of surveillance effectiveness.

Table 4.2: Effect of tower height on camera viewing width

Tower height (m)	Viewing width (m)
10	11.55
50	57.74
100	115.47

Fibre-Optic Performance Analysis

The fibre-optic attenuation was estimated using an assumed attenuation coefficient of 0.35 dB/km. For the calculations presented in Table 4.3, the corresponding fibre lengths were assumed to be equal to the stated distances of 10, 50, and 100 m. These fibre lengths are independent of tower height; in a practical installation, the actual cable route between the tower and the control room must be used.

The results show that the estimated fibre attenuation increases with fibre length. The attenuation rises from 0.0035 dB at 10 m to 0.0350 dB at 100 m. These values indicate that the assumed fibre attenuation contributes only a small loss over the short distances considered.

This characteristic supports the suitability of fibre-optic communication for transmitting surveillance data between equipment located on the tower and nearby communication infrastructure. Nevertheless, total optical link loss also depends on the operating wavelength, fibre specifications, connectors, splices, bending losses, and other optical components.

Table 4.3: Estimated fibre-optic attenuation at selected fibre lengths

Assumed fibre length (m)	Fibre attenuation (dB)
10	0.0035
50	0.0175
100	0.0350

Optical Power Analysis

The optical link performance was assessed using a transmitter power of 0 dBm and a receiver sensitivity of −28 dBm. The gross optical power budget is:

$$P_{\text{budget}} = P_t - P_{\min} = 0 - (-28) = 28 \text{ dB} \quad (15)$$

where P_t is the transmitter optical power (dBm) and $P_{\min}$ is the receiver sensitivity (dBm).

The gross budget of 28 dB represents the maximum total link loss before the received power reaches the receiver sensitivity. However, the practical usable budget is lower because connector/splice losses and an engineering reserve must be deducted. Using the assumed 2 dB combined connector/splice loss and 3 dB engineering margin from Table 3.1:

$$L_{\text{usable}} = 28 - 2 - 3 = 23 \text{ dB} \quad (16)$$

Using the assumed attenuation coefficient of 0.35 dB/km, the corresponding distances are:

i. Ideal theoretical maximum fibre distance (gross budget, zero additional losses):

$$L_{\text{max,ideal}} = \frac{28}{0.35} = 80 \text{ km}$$

ii. Adjusted maximum fibre distance (practical budget after 2 dB component losses and 3 dB engineering margin):

$$L_{\text{max,adjusted}} = \frac{23}{0.35} = 65.71 \text{ km}$$

The 80 km value is an ideal theoretical upper bound. The 65.71 km value is the estimated maximum fibre

distance under the stated assumptions. Neither value is a guaranteed practical deployment distance; actual reach depends on the selected transceivers, operating wavelength, fibre characteristics, connector and splice quality, bending losses, and installation conditions.

Maximum Transmission Distance

The maximum transmission distance was estimated using the optical power budget and the assumed fibre attenuation coefficient. Under idealized conditions (zero connector/splice losses and zero engineering margin), the gross 28 dB budget gives a theoretical upper bound of approximately 80 km. Including the assumed 2 dB connector/splice loss and 3 dB engineering margin, the budget-limited maximum fibre reach under the stated assumptions is approximately 65.71 km.

The estimated distance suggests that the proposed fibre-optic communication architecture could support remote placement of the control room, provided that the selected optical transceivers and other link components support the required transmission distance. The practical distance will depend on the total optical link budget, operating wavelength, fibre characteristics, connector and splice losses, receiver sensitivity, and required engineering margin.

Signal Quality Analysis

Signal-to-noise ratio (SNR) and bit error rate (BER) were considered as general indicators of communication quality. However, quantitative evaluation of these parameters was not undertaken because the receiver noise model, operating bandwidth, modulation format and detection architecture were not sufficiently specified. Consequently, no numerical SNR or BER performance is claimed for the proposed platform.

A sufficiently high SNR generally supports more reliable digital signal detection, while a lower BER indicates fewer transmission errors. These parameters are relevant to security surveillance because reliable communication is required for the transmission of video streams, motion-detection events, and system alerts. However, the available design parameters do not include a fully specified receiver noise model, modulation format, or measured SNR and BER values.

Assessment of Optimal Tower Height

The effect of increasing tower height on selected engineering and operational factors was assessed qualitatively. The results are summarized in Table 4.4.

Table 4.4: Qualitative assessment of tower height

Factor	Expected effect of increasing height
Theoretical coverage radius	Increases
Theoretical coverage area	Increases
Camera ground viewing width	Increases for a fixed field of view and downward orientation
Wind loading	Increases
Structural requirements	May increase
Construction and installation cost	May increase
Maintenance requirements	May increase
Fibre signal quality	Depends primarily on the communication link budget
Power consumption	Depends on equipment and system configuration

The analysis indicates that increasing tower height expands the theoretical coverage radius and area. However, greater height may also increase wind loading, foundation requirements, structural complexity, installation costs, and maintenance demands. These factors must be considered when selecting a practical tower height for security surveillance.

Based on the preliminary design assessment, a height range of 60–70 m was proposed for further evaluation. This range represents a candidate design option rather than a mathematically established optimum. The final selection should be supported by structural analysis, a detailed cost assessment, coverage requirements, and the expected surveillance performance.

Furthermore, tower height alone does not determine fibre-optic signal quality. Signal quality is principally governed by the optical transmitter, receiver, fibre characteristics, link length, and associated losses. Therefore, the proposed height range should be evaluated using a multi-criteria design approach rather than assuming that it automatically provides the best balance of coverage, cost, and reliability.

Solar Power System Results

The estimated average electrical load of the surveillance and communication equipment is presented in Table 4.5. The connected rated load is 430 W, and the average operating load, after applying the assumed load factors, is 160 W.

Table 4.5: Estimated average electrical load of the surveillance system

Equipment	Estimated average power (W)
4K IP CCTV cameras (4 units)	80
Thermal camera	10
Network switch and optical transceiver	40
AI processing unit	15
Sensors and electronics	15
Total average load	160

The average operating load is calculated as:

$$P_{\text{avg}} = 80 + 10 + 40 + 15 + 15 = 160 \text{ W} \quad (17))$$

Assuming continuous operation over 24 hours, the daily energy requirement is:

$$E_{\text{daily}} = 160 \times 24 = 3{,}840 \text{ Wh/day} \quad (18)$$

Using the sizing equations and design inputs from the Methodology (Equations 13–14; Table 3.3), the calculated PV array requirement is approximately 1.138 kWp at 5 peak-sun-hours, a 0.75 system efficiency and a 0.90 battery charging efficiency. A preliminary nominal PV array rating of 1.2 kWp is proposed**,** subject to site-specific solar-resource and system-performance validation.

For battery autonomy, the DC-coupled configuration (Equation 14) gives:

- 48-hour autonomy: 48 V, 211 Ah (approximately 10.1 kWh nominal).
- 72-hour autonomy: 48 V, 316 Ah (approximately 15.2 kWh nominal).

A nominal 10 kWh battery provides approximately 47.5 hours of operation at an average load of 160 W when an allowable depth of discharge of 80% and a battery discharge efficiency of 95% are assumed. This estimate does not include additional DC conversion losses. Consequently, the nominal 10 kWh battery does not fully satisfy the 48–72-hour backup target under the adopted assumptions. The battery capacity should be increased to approximately 15.2 kWh for 72-hour autonomy, or the autonomy target revised to 48 hours.

Table 4.6: Proposed solar-hybrid power system specifications

Component	Proposed specification
Solar PV array	1.2 kWp (preliminary)
Battery bank	48 V, 211 Ah (48 h) to 316 Ah (72 h); approximately 10.1–15.2 kWh nominal
Charge controller	MPPT, rated for array current
Target backup autonomy	48–72 hours
Energy storage technology	$LiFePO_4$ battery

Note: The surveillance equipment operates directly from the 48 V DC bus. An inverter is not included in the proposed configuration. If an inverter is later retained for auxiliary AC equipment, its purpose and the associated AC loads must be identified, and the inverter losses must be included in the energy balance.

The battery calculations assume that the average 160 W load already accounts for the power delivered to the equipment. If DC-DC converters or Power over Ethernet (PoE) interfaces introduce additional losses that are not included in the load estimates, the battery capacity must be recalculated.

These are preliminary analytical design estimates based on assumed inputs. They are not experimentally validated or installed equipment specifications. The final PV array and battery bank must be selected after the equipment power ratings, local solar resource and battery manufacturer specifications have been verified.

Summary of System Performance

The principal performance indicators and their status are summarized in Table 4.7.

Table 4.7: Summary of analytical results and design estimates

Performance indicator	Result or estimate	Interpretation
Theoretical coverage area	Approximately 400–4,003 km²	Increases with tower height under the adopted geometric model
Camera ground viewing width	11.55–115.47 m	Increases linearly with height for a fixed 60° field of view

Fibre attenuation	0.0035–0.035 dB	Calculated for assumed fibre lengths of 10–100 m
Gross optical power budget	28 dB	Available budget before practical link losses
Usable fibre attenuation budget	23 dB	After 2 dB component loss and 3 dB engineering margin
Ideal theoretical maximum fibre distance	80 km	Based on 28 dB gross budget and 0.35 dB/km attenuation
Adjusted maximum fibre distance	65.71 km	Based on 23 dB usable budget and 0.35 dB/km attenuation
Signal-to-noise ratio	Not quantitatively established	Requires a defined receiver noise model
Bit error rate	Not quantitatively established	Requires an appropriate communication model or measurements
Connected rated load	430 W	Sum of rated power of all equipment
Average operating load	160 W	After applying assumed load factors
Daily energy consumption	3.84 kWh/day	Assumes continuous 24-hour operation
Proposed preliminary PV capacity	1.2 kWp	Preliminary analytical estimate; requires validation
Battery capacity for 48-hour autonomy	Approximately 10.1 kWh nominal (48 V, 211 Ah)	Theoretical estimate under stated assumptions
Battery capacity for 72-hour autonomy	Approximately 15.2 kWh nominal (48 V, 316 Ah)	Theoretical estimate under stated assumptions
Candidate tower height	60–70 m	Requires structural, economic, and coverage validation

CONCLUSION

This study has presented an analytical evaluation of a solar-powered, elevated-tower fibre-optic communication platform for security surveillance. The results show that increasing tower height expands the theoretical line-of-sight coverage radius, geometric coverage area and camera ground viewing width. The estimated fibre attenuation remains low over the assumed cable distances, while the adjusted optical link budget gives a theoretical maximum fibre distance of 65.71 km under the adopted assumptions. The estimated average electrical load of 160 W corresponds to a daily energy requirement of 3.84 kWh, providing a basis for preliminary solar power system sizing. A PV capacity of 1.2 kWp and a battery capacity of approximately 10.1–15.2 kWh is proposed for the intended 48–72-hour backup period. A tower height range of 60–70 m is identified as a candidate design option rather than a proven optimum. The findings provide an analytical basis for further system development; however, field testing and additional engineering assessments are necessary to establish the practical performance, reliability and suitability of the proposed platform.

Recommendations

Future work should involve field validation of the model through measurements of actual surveillance coverage, camera performance, fibre-optic link characteristics and electrical power consumption. Structural and economic assessments should also be conducted to determine the suitability of the proposed tower heights under practical operating conditions. Further studies may employ machine-learning and optimisation techniques to investigate suitable tower heights, camera positions, optical link parameters and solar power configurations. These investigations would help improve surveillance coverage, communication reliability and energy efficiency.

AI Disclosure Statement

Use of Artificial Intelligence Tool

An artificial intelligence tool (ChatGPT) was used to assist in generating computational algorithms and modeling workflows. The authors defined all system parameters, verified the generated algorithms, and conducted the final analysis and interpretation of the results.

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