reduced false alarms by 28 % and improved alert accuracy to 96 %, confirming its robustness against environmental fluctuations.

Field validation demonstrated tangible operational benefits. The AI framework forecasted a 7 % performance drop due to dust accumulation three days in advance, enabling timely cleaning and avoiding energy losses. During a heatwave event, it predicted a 15 °C hotspot rise 24 hours earlier, allowing pre-emptive load redistribution and avoiding thermal damage.

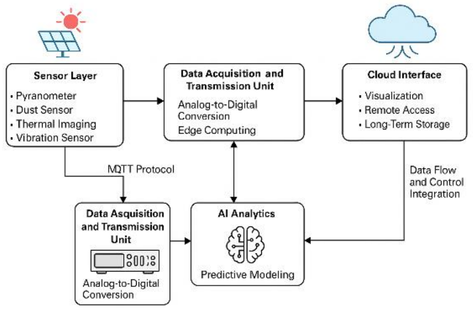


Figure 1 – Schematic representation of the modular AI-driven instrumentation framework for predictive maintenance of solar PV and thermal collector systems

System-level deployment reduced unscheduled downtime by 37 % and temperature-induced stress cycles by 21 %, extending subsystem service life by approximately 2.3 years. The AI-monitored 5 kW array produced 5.6 % more annual energy than the control, yielding an additional 613 kWh per year and saving about 0.45 t $CO_2$ emissions. Economically, maintenance costs fell by 19 %, halving emergency interventions and shortening the return-on-investment period from 36 to 22 months.

These results confirm that fusing multi-sensor data with AI analytics enhances the reliability, efficiency, and financial sustainability of solar PV–thermal installations in smart-grid environments.

**Conclusion.** This study demonstrated the effectiveness of a hybrid AI-driven predictive maintenance framework combining Long Short-Term Memory (LSTM) and Random Forest (RF) algorithms integrated with IoT-based multi-sensor instrumentation for solar PV and thermal collectors. The system improved operational reliability, achieving 37 % lower downtime, 21% reduction in thermal stress cycles, and a 5.6 % annual energy-yield gain. Economic analysis revealed a 19 % cost reduction and a shortened ROI of 22 months, confirming both technical and financial viability.

Future work should focus on scaling the framework through cloud-edge orchestration, cross-climate model transfer, and integration with digital-twin architectures for adaptive, self-learning maintenance. Expanding to include real-time LCOE tracking, cybersecure communication, and lifecycle carbon assessment will further enhance decision-making for intelligent, sustainable solar infrastructures.

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## FREE-SPACE OPTICS BACKHAUL: A STRATEGIC NECESSITY FOR 5G AND 6G ROLLOUT WITHIN ZIMBABWE'S EMERGING TELECOM ENVIRONMENT

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**Abstract.** In 2024, Zimbabwe's mobile data traffic grew by 35 %, which put a lot of stress on the backhaul infrastructure [1]. Microwave links have limited capacity, and fibre is expensive in rough terrain. Free-Space Optics (FSO) is a solution that uses light beams to send data at speeds similar to fibre optics. This makes it possible to quickly deploy 5G and 6G in both rural and urban areas. This work suggests using both FSO and millimetre-wave systems together to make sure that the network stays reliable even in bad weather. This will make it easier to expand the network and offload.

**Keywords:** Free-Space Optics (FSO), 5G Backhaul, 6G Networks, Hybrid Systems, Digital Divide.

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**Introduction.** 5G and 6G networks call for very high-capacity and low-latency backhaul to support applications like broadband speeds, smart industry, and connected devices [2]. Mobile data demand is growing quickly in Zimbabwe. Mobile data traffic grew by 35 % in 2024, while internet access capacity grew by 22.3 % [1]. The most reliable backhaul comes from fibre optic cables but is expensive to install in mountainous and rural areas. It is very expensive, for example, to connect the Eastern Highlands and other remote parts of Zimbabwe with fibre. Microwave links are cheaper and easier to install but cannot always provide the capacity required for 5G [3].

FSO is a solution. Data is transmitted along the air via light using narrow beams, with data rates of 10 Gbps or more [5]. FSO is less costly and simpler to install than fibre, making it perfect for rural areas that are hard to reach, as well as in urban small-cell networks.

**How FSO Meets 5G and 6G Requirements.** FSO can achieve extremely high speeds (10 Gbps in commercial roll-out, and even higher in trials) [5]. It also has extremely low delay (latency), which is beneficial for real-time applications such as industrial control and intelligent transport [6]. FSO does not involve trenching or cabling. It has the ability to link sites over mountains, valleys, or woods where fibre is too expensive. That makes it valuable for rural areas in Zimbabwe that are presently underserved. In the cities like Harare and Bulawayo, demand for data overloads cellular networks. 5G requires large numbers of small cells, each having strong backhaul. Fibre installed in abundance for every small cell is slow and invasive. FSO can connect them in a rush, decongesting cities [7].

**Hybrid FSO Solutions and Reliability.**

FSO is affected by fog, rain, and turbulence, which distort the signal. This is an issue in Zimbabwe during rainy seasons. The best solution is to integrate FSO with Millimetre-Wave (MMW) links. FSO works best in clear weather, while MMW works well in fog conditions. They provide a strong backhaul system with high availability [6, 8]. Future networks will be able to use smart systems for monitoring weather and switching between FSO and MMW before service interruption [7]. FSO will also facilitate the interconnection of earth stations with satellites or high-altitude platforms and help in extending coverage to very remote areas [9].

**Benefits in Zimbabwe.** Rural coverage connects rural areas and rough terrains without costly fibre (e.g., Eastern Highlands). Digital divide in which fast deployment for schools, clinics, and villages to extend internet to underserved communities. Urban congestion that supports many 5G small cells, relieving traffic in Harare and Bulawayo 5G is cost-efficient and cheaper than trenching fibre, enabling operator expansion 5G brings security than because narrow beams are hard to intercept, making them useful for sensitive communications.

**Policy Recommendation.** POTRAZ and Mobile Network Operators must pilot FSO in urban areas to underpin 5G small cells in Harare. In rural areas and mountainous areas like the Eastern Highlands, they should spearhead hybrid FSO/MMW links, with a year's monitoring to get performance data.

**Conclusion.** FSO can help Zimbabwe expand 5G backhaul capacity and prepare for 6G. It is especially useful in challenging terrain, where fibre is too expensive, and in urban areas, where networks are congested. Hybrid FSO/MMW systems reduce weather risks, making them suitable for application in the telecommunication industry.

Limitation: There is little data on how FSO performs under Zimbabwe's specific weather conditions. Pilot projects are needed to confirm its reliability and cost-effectiveness before nationwide rollout.

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