Multi-Band Heterogeneous Wireless Network Architecture for Industrial Automation: A Techno-Economic Analysis

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Abstract
To attain automation across different applications, industries are beginning to leverage advancements in wireless communication technologies. A “one-size-fits-all” solution cannot be applied since wireless technologies are selected according to application needs, quality of service requirements, and economic restrictions. To balance the trade-off between technical and economic requirements, a multi-band heterogeneous wireless network architecture is presented and discussed in this paper. Wireless local area network (WLAN) and distributed antenna system (DAS) with Long Term Evolution (LTE) are considered as the backbone for the multi-band heterogeneous network into which other wireless technologies can be integrated. The technical and economic feasibility of the network are evaluated through a techno-economic analysis (TEA). The economic feasibility of the proposed network is measured in terms of net present value while the technical feasibility is measured in terms of network throughput and latency. Finally, network performance for DAS with LTE and WLAN are verified using an NS3 simulator for machine-to-machine, real-time video, and high-definition video data transmissions. The TEA analysis showed that the number of DAS units required to achieve technical feasibility is less than WLAN units, but the overall cost of DAS units are higher compared to WLAN units, even without taking into consideration industrial, scientific, and medical band technologies.

Keywords Distributed antenna system · Techno-economic analysis · Wireless network · Quality of service

1 Introduction
Industries are moving toward implementing advanced technologies to automate monitoring, inspection, security, and other tasks to enhance their operating efficiency and effectiveness without compromising on safety and reliability. Wired solutions enable reliable
data transmission but their deployment costs are extremely high. Industrial automation is becoming a reality with the emergence of 5G technology, along with several advanced low-power Internet of Things (IoT) technologies [1]. Most wireless technologies available today, such as wireless local area network (WLAN) [2], Bluetooth, Zigbee, and radio frequency identification (RFID), use the 2.4GHz and industrial, scientific, and medical (ISM) band. The Long-Term Evolution (LTE)-based solutions, such as Narrow Band (NB)-IoT, Category-1 (Cat-1), and Category-M (Cat-M) are also evolving as low-energy and low bit-rate solutions for IoT applications. In addition, the proprietary technologies, such as, long-range wide area network (LoRaWAN) and RFID are making their mark in IoT applications using unlicensed spectrum bands (such as 900MHz, 2.4 GHz, etc.) with simple and cost-effective deployments.

With a diversity of wireless technologies available today, it is not possible to develop a “one-size-fits-all” solution to enable industrial automation. Different types of data are transmitted over a wireless network with different quality of service (QoS), latency, and bandwidth requirements [3]. Hence to satisfy industrial automation and communication needs, co-existing networks resulting in a heterogeneous network is highly desired. To deploy multiple wireless technologies, signal degradation at different levels and interference between technologies should be considered. This helps to identify the required number of antennas or access points (APs) to be placed at different sections of the industrial environment for improved coverage and capacity. In this regard, distributed antenna (DA) technologies such as Distributed Antenna System (DAS) and WLAN are widely used in industrial communication. DAS is widely used to provide cellular connectivity in indoor and outdoor environments. In industrial environment, either WLAN or cellular networks integrated to DAS unit will be used to upload and offload data to a cloud or remote location for data analysis, monitoring, diagnosis, and prognosis.

Besides technical considerations, regulatory, economic, and competitive aspects are also key to creating a feasible network without compromising on the desired performance [4]. In this regard, a techno-economic analysis (TEA) can be used to connect research and development, engineering, and business units. More importantly, a TEA can examine feasibility of a technology, cost benefit studies, risks and uncertainties, offering a basis for site owners to make objective decisions regarding a technology deployment. An accurate and practically effective TEA approach takes into consideration technical parameters and computes cost-effective way to offload and upload data based on data traffic types, priorities, bandwidth, power consumption, and distance.

The contributions made through this work are the following:

A. A multi-band heterogeneous wireless network architecture (Fig. 1) that can support industrial automation is proposed. The proposed network integrates ISM-band technologies and cellular LTE into a DAS unit, with improved coverage and capacity along with WLAN deployed in parallel. A centralized data collection, controls, and monitoring of all the technologies is enabled through cloud. The proposed wireless network would enable applications from low- to high-power, low- to high-frequency range, and short- to long-range communication requirements. The ISM technologies, such as LoRaWAN and RFID, are integrated into the DAS structure so that multiple wireless technologies are included under one network architecture. The network architecture can also support integration of mmWave communication and Bluetooth wireless technologies. To the best of authors knowledge, no other multi-band heterogeneous networks in literature are enabling these capabilities.

B. A TEA framework has been developed, which not only considers market costs of network components but also takes aspects such as network coverage and capacity into
account. Coverage parameters capture signal degradation aspects in different environment conditions, whereas capacity parameters consider user demands that need to be full filled by the proposed network with satisfactory QoS. C. Along with the analytical results on the network performance, the proposed network architecture (DAS and WLAN networks) is tested in terms of average throughput and average delay using an NS3 simulator for different data traffics, attenuation levels, and other conditions.

The remainder of the article is organized as follows. Related literature on TEA of wireless technologies and networks along with main contributions of this work are covered in Sect. 2. The proposed network architecture is described in Sect. 3. A TEA framework is presented in Sect. 4. Section 5 presents the evaluation of the TEA framework for DAS and WLAN networks. A numerical analysis of network dimensioning, cost analysis, and network performance and capability using an NS3 simulator is presented in Sect. 6. Finally, conclusions are drawn and future research directions are identified in Sect. 7.

2 Related Work

A detailed survey on wireless networks for industrial automation is studied in [5] with focus on QoS and security. Survey studied implementation of advanced wireless technologies such as WirelessHART, International Society of Automation (ISA)-100.11a, ZigBee, ZigBee PRO, and Institute of Electrical and Electronics Engineers (IEEE) 802.15.4e for industrial automation. The survey doesn’t discuss the coexistence of these networks. An IEEE 802.11 based isochronous wireless network is presented in [6] to provided seamless connectivity and sufficient capacity for real-time communication in industrial control applications. Similarly, an LTE Advanced-Pro and 5G based wireless network in terms of modified picocell and modified distributed antenna systems are presented in [7] and [8], respectively and a comparative study is reported on IEEE 802.11an/ac protocols. The recent works [9, 10] focused on evaluating cost effective feasibility of using LTE wireless networks in energy grids to reduce operational expenditure as well greenhouse gas emission in the telecommunications sector.

Ethernet Passive Optical Network (EPON) and Wireless Interoperability Microwave Access (WiMAX) are considered as the key technologies in hybrid Fiber-Wireless networks [11, 12]. TEA models were developed by taking into consideration both equipment
and installation, and operation and maintenance (O&M) costs for a wide range of network failure scenarios, terrain types, and wireless channel conditions. The key finding of the work is that power consumption of EPON is less than that of WiMAX. The operational expenditure (OPEX) of EPON is superior to WiMAX [13] due to less unlikely network failures. Taking both capital expenditure (CAPEX) and OPEX into account, WiMAX is cost efficient than EPON in suburban and rural areas with a moderate population density. Whereas the TEA on bringing wireless access into rural as well as urban areas by leveraging small cells and edge cloud technologies are studied to address the identified limiting market conditions [14].

To meet higher data traffic demands in a cost effective way, heterogeneous wireless networks comprised of Macro-Micro, Macro-Pico, Macro-WLAN [15], and Macro-Femtocell [16] infrastructures are considered. A study was performed by taking into account discounted cash flow with the total cost of ownership (TCO), to determine which of the four infrastructures is the most economical way to offload data in a heterogeneous wireless network, depending on the kind of data traffic. Researchers in [17] determined that, with the increased traffic load, the CAPEX and OPEX costs make Macro-Femtocell a superior infrastructure.

To meet required data rates and round-trip times for indoor mobile subscribers promised by next-generation mobile networks, a study on TEA of ultra-dense (femtocells) and DAS deployments was performed [18]. The model considers both CAPEX and OPEX based on used bandwidth requirements. The work concluded that the TCO associated with the DAS deployment is higher than the femtocells.

3 Network Architecture

The proposed network architecture (Fig. 1) is predominantly driven by DAS or WLAN systems. The following section summarizes features and components of the proposed wireless network architecture.

3.1 Distributed Antenna System

LTE signals from multiple carriers are filtered, attenuated, and controlled at the BS interface (Fig. 1). The radio frequency (RF) signal is then converted into an optical signal for distribution through optic fiber using an optical distribution unit. At the mid-power remote optic unit, the optic signal is distributed to independent amplifiers of different frequency bands, and all the amplifier outputs are combined using an RF combiner into a single output signal. The signal is distributed to several antenna units installed in and around the monitoring area [19]. The DAS supports multiple frequencies to include 700 MHz, 1900 MHz, and advanced wireless services frequencies for LTE [20], along with ISM-band technologies. DAS offers a single-zone wireless coverage without intercell-interferences and handoffs. In this research, a digital DAS system from [19] is considered.

3.2 Wireless Local Area Network

The WLAN [2] capable of providing a high data rate internet connection, is made up of low coverage and limited capacity APs operating at an unlicensed spectrum of 2.4 GHz
and 5 GHz. To fulfill the coverage and capacity requirements, the WLAN provides the network capacity by distributing wireless APs with limited frequencies around the monitoring area. Since WLANs operate at unlicensed bands, interference from neighboring APs with appropriate power transmission control is observed. The sixth-generation wireless fidelity standard IEEE 802.11ax [2], also called as WiFi-6, is the latest step in the WLAN advancement. One of the aims to develop WiFi-6 is to support flexible and scalable applications; thereby, making way for new and existing networks to power next-generation applications. WiFi-6 has an enhanced network throughput due to advanced orthogonal frequency division multiple access (OFDMA) and multi-user multi-input multi-output (MU-MIMO) with beam-forming capability at higher modulation of up to 1024-quadrature amplitude modulation (QAM). WiFi-6 can transmit eight different spatial streams simultaneously, and supports low-power and low-bandwidth applications.

### 3.3 Industrial, Scientific, and Medical Band Technologies

Several wireless technologies, such as LoRaWAN and RFID, operate in an unlicensed ISM-band (900 MHz in North America) for low-power, low-bit rate, and long-range applications. Each technology has its own physical layer design, medium access control layer protocols, and security algorithms. These technologies along with other networks (such as Bluetooth Low Energy and Zigbee) and sensors modules (such as video surveillance or mmWave radar modules) can be integrated along with cellular technology using a DAS structure.

### 4 Techno-Economic Framework

Technical parameters such as network density are utilized to assess the economic feasibility of the proposed wireless network architectures in Fig. 1. Figure 2 depicts the TEA flow diagram for the proposed wireless network architecture. Within this architecture, different services such as sensor data uploading, surveillance, O&M, and monitoring can be achieved over a wireless network infrastructure. The TEA framework performs network modeling to determine the number of APs for WLAN or distributed antennas (DAs) for DAS required in a service area with desired network capacity.

#### 4.1 Network Economic Indicators

Two network economic performance indicators are used in this paper. The TCO (i.e., sum of CAPEX and OPEX) and the net present value (NPV).

TCO defines the total network deployment expenditure, including hardware purchasing, site acquisition, spectrum commissioning, integrating the network to the core network, operating, upgrading (direct and indirect), and maintenance over a specific time period. TCO is also an effective approach to assess the profitability of an entire network structure over its life cycle by providing an estimated calculation model for each of the network components under different cost structures. TCO comprises two main categories: CAPEX and OPEX. Each expenditure can be considered individually to estimate the final TCO.
The CAPEX includes the purchase of network equipment, network installation costs (labor costs), network infrastructure costs (e.g., cabling), and network management costs. The OPEX covers the power consumption, troubleshooting, maintenance and repair service costs, operational network planning costs (e.g., day-to-day planning, optimization, and upgrade), and human resource costs (e.g., wages and salaries).

The NPV based on assumptions that future cash flow values are known and discounted at risk-adjusted factor, is expressed as,

$$NPV = \sum_{i=1}^{n} \frac{CF_i}{(1 + \gamma)^i}$$

where $CF_i$ is the net difference of cash inflow and cash outflow during the $i^{th}$ discount rate, $n$ is the number of cash flows, and $\gamma$ is the discount rate. Here cash inflow refers to total cost saving after network deployment, and cash outflow refers to network deployment and maintenance costs. A positive NPV indicates profitable deployment of a technology.

4.2 Network performance indicators

Throughput and latency are the two network performance indicators used to evaluate the performance of the proposed wireless network architecture. These network performance indicators must be able to meet different applications requirements under different operating environments.

4.2.1 Throughput

For a network using the Transmission Control Protocol (TCP), the rate of successful data transmission is determined by
where $RTT$ is the round-trip time to send data and receive acknowledgement back. The proposed wireless network architecture utilizes the TCP.

### 4.2.2 Latency

At a given time instance, the data transmitted over the network can come from multiple users of the same or different applications. This might result in congestion or collision possibility, resulting in a data packet loss. To minimize the data packet loss, the network is required to transmit the data packet within a specified expected latency. For a network of $N$ active users/nodes transmitting data at the rate of $\lambda$ bits/sec over a channel with maximum capacity of $W_{\text{max}}$ bits/sec, the average waiting time per data packet, denoted as $E[W]$, of size $K$ bytes is given by [21],

$$E[W] = K \left( \frac{\rho^2}{(1-\rho)\lambda} + \frac{1}{W_{\text{max}}} \right) \text{ seconds}$$

where $\rho = \frac{\lambda}{W_{\text{max}}}$ is the network utilization parameter. Note that, if $E[W] > W_{\text{threshold}}$, the maximum tolerable delay, the packet will be dropped or discarded.

### 5 Techno-Economic Evaluation

In this section, a TEA for the proposed wireless network architecture with main focus on WLAN and DAS deployments is presented.

#### 5.1 WLAN Deployment

The cost model for WLAN mainly depends on the number of APs distributed as per a network design. WLAN consists of an access gateway and a router that is required to be connected to the network backhaul using co-axial cables such as RG-6 [22]. Typical WLAN components include mainly APs, routers, switches, cables, and a network backhaul. Given these details, the cost model in terms of CAPEX and OPEX for a WLAN deployment is discussed here.

#### 5.1.1 CAPEX

The CAPEX cost for WLAN is driven by the cost of an AP. Let $C_{\text{AP}}$ represent the cost of a single AP. Cost associated with additional equipment needed to install and connect an AP to the network backhaul is represented as $C_{eq,W}$. The installation cost per AP, including labor charges, is represented as $C_{\text{inst}}$. The CAPEX for a WLAN with $N_{\text{AP}}$ APs is expressed as,

$$C_{\text{CAPEX}}^{\text{WLAN}} = N_{\text{AP}}(C_{\text{AP}} + C_{eq,W} + C_{\text{inst}}) + C_{\text{sec,W}}$$

where $C_{\text{sec,W}}$ represents the combined costs of software installation and security firmware.
5.1.2 OPEX

OPEX represents the day-to-day operation of the system, including power consumption, annual subscription, and O&M costs of WLAN components. The running cost (including repairs or replacements) of a WLAN system with single or multiple failures is given by:

$$C_{R-WLAN} = \sum_{i} \alpha_{i,WLAN} P_{f_i,WLAN} \times C_{CAPEX}^{WLAN}(i)$$

(5)

Here, $\alpha_{i,WLAN}$ represents the repair or replacement rate of the $i$-th failed WLAN equipment. $P_{f_i,WLAN}$ represents the probability of failure of the $i$-th WLAN equipment with the initial installation cost of $C_{DAS}^{WLAN}(i)$. The per-year power consumption cost of an AP and other WLAN components is given by $C_{AP,P}$ and $C_{eq,P}$ respectively. Therefore, the total power consumption cost of an entire WLAN network is expressed as $C_{W,P} = C_{AP,P} + C_{eq,P}$. Let $C_{om}$ represent the annual O&M costs, including the subscription cost. The total OPEX for a WLAN system with multiple APs is expressed as,

$$C_{OPEX}^{WLAN} = N_{AP}(C_{R-WLAN} + C_{W,P} + C_{om})$$

(6)

The TCO per annum of a WLAN can be expressed as:

$$TCO_{WLAN} = C_{CAPEX}^{WLAN} + C_{OPEX}^{WLAN}$$

(7)

5.2 DAS deployment

The cost model for a DAS with and without ISM technologies is presented here briefly. The details of the cost model are captured in [4]. The DAS plus ISM-band structure cost parameters and their descriptions are listed in Table 1.

5.2.1 CAPEX

The CAPEX for a DAS with $N_{bh}$ LTE cellular network, denoted as $C_{CAPEX}^{DAS(LTE)}$, with all its components is,

$$C_{CAPEX}^{DAS(LTE)} = N_{bh}(C_{BS} + C_{EPC}) + C_{eq,D} + N_{DA}(C_{RU} + C_{DA})$$

(8)

ISM-band technologies such as RFID and LoRaWAN are included into DAS system using an ISM-band interface card at the gateway backhaul. Thus the total CAPEX of ISM-band technologies RFID and LoRaWAN is given by

$$C_{CAPEX}^{ISM} = N_{g}C_{g} + C_{sec,LW} + C_{eq,ISM} + N_{f}C_{r} + C_{eq,R}$$

(9)

Finally, the total CAPEX for a DAS structure is expressed as,

$$C_{CAPEX}^{DAS} = C_{CAPEX}^{DAS(LTE)} + \mathbb{I} \cdot C_{CAPEX}^{ISM}$$

(10)

Here, $\mathbb{I}$ is the indicator function that is used to capture the inclusion ($\mathbb{I} = 1$) or exclusion ($\mathbb{I} = 0$) of ISM-band technologies.
5.2.2 OPEX

OPEX due to (1) failure of DAS components; (2) damages in fiber cable distribution; (3) annual power consumption, (4) backhaul maintenance [18] and (3) additional interface failure, such as LoRaWAN or RFID, etc, is given by [4]:

\[
C_{R-DAS} = \sum_{i} \alpha_{i,DAS} P_{f_i,DAS} \left( C_{CAPEX,DAS}^{i} \right) + C_P + f_{BW} \times BW
\]

\[
+ \Pi \cdot \alpha_{i,ISM} P_{f_i,ISM} \left( C_{CAPEX,ISM}^{i} \right)
\]

(11)

where \(i\) denotes the \(i\) – th failed equipment that either needs to be repaired or replaced. Also, \(P_{f_i,DAS}\) and of the \(i\) – th denote the probability of failure of the \(i\) – th DAS equipment and \(i\) – th ISM equipment, respectively. In Eq. (11), \(\alpha_{i,DAS}\) and \(\alpha_{i,ISM}\) represent the repair or replacement rate of the failed \(i\) – th DAS equipment and of the failed \(i\) – th ISM equipment respectively. When \(\alpha_{i,\cdot} = 0\) (\(\alpha_{i,\cdot} = 1\)) the equipment is repairable (irreparable and must be replaced).

Thus, TCO per annum of a DAS+ISM structure can be expressed as:

\[
TCO_{DAS} = C_{CAPEX,DAS}^{\cdot} + C_{OPEX,DAS}^{\cdot}
\]

(12)
Numerical simulations are performed using an NS3 simulator to evaluate network performance of DAS and WLAN deployment under different operating scenarios along with network cost analysis based on the TEA presented in Sects. 4 and 5. Using the formulations presented in Sect. 5, numerical results are estimated on how the network cost varies as a function of traffic demand and environment type. Tables 2 and 3 present the cost structures for DAS and WLAN model parameters based on current market values. Some of the cost values (for example, the cost of LoRaWAN gateway) are approximates, but should be representative in a relative sense. The cost values summarized in Tables 2 and 3 are not actual market values because they depend on the time, geolocation, market, and other factors. Similarly, the network performance present in the paper is a general estimate and do not represent the performance of any particular product. For numerical assessment of a DAS with and without ISM and of WiFi-6, an area of $100 \times 100 m^2$ is considered for network deployment with three types of environments. These include moderately open, slightly dense, and moderately dense. The moderately open environment exhibits RF signal

### Table 2  DAS structure equipment and installation cost parameters

| Parameters | Description | Cost/Values |
|------------|-------------|-------------|
| $C_{BS}$   | Cost of a BS | $1100$ [18] |
| $C_{EPC}$  | Cost of an EPC | $120$ [18] |
| $BW$       | EPC bandwidth | $100$Gbps [18] |
| $f_{BW}$   | Cost per bandwidth | $1200$ |
| $C_{eq.D}$ | DAS equipments cost | $13,000$ [23] |
| $C_{DA}$   | DAS antenna cost | $200$ [23] |
| $C_{RU}$   | Cost of an RU | $3178$ [23] |
| $C_{g}$    | Cost of a LoRaWAN gateway | $800$ [24] |
| $C_{sec.LW}$ | Security firmware cost | $5000$ |
| $C_{t}$    | Cost of an RFID transducer | $475$ [25] |
| $C_{p}$    | Per year DAS power consumption cost | $10,000$ |
| $C_{eq.ISM}$ | ISM integration cost | $3000$ |
| $C_{eq.R}$ | RFID integration cost | $3000$ |

### Table 3  WLAN structure equipment and installation cost parameters

| Parameters | Description | Cost/Values |
|------------|-------------|-------------|
| $C_{AP}$   | Cost of an AP | $1250$ [26] |
| $C_{om}$   | O&M cost | $10,000$ |
| $C_{inst}$ | Per AP installation cost | $100$ |
| $C_{eq.W}$ | WiFi equipment cost (routers, switches, etc.) | $50$ |
| $C_{AP.p}$ | Per year AP power consumption cost | $200$ |
| $C_{eq.P}$ | Per year equipment power consumption cost | $100$ |

## 6 Numerical results

Numerical simulations are performed using an NS3 simulator to evaluate network performance of DAS and WLAN deployment under different operating scenarios along with network cost analysis based on the TEA presented in Sects. 4 and 5. Using the formulations presented in Sect. 5, numerical results are estimated on how the network cost varies as a function of traffic demand and environment type. Tables 2 and 3 present the cost structures for DAS and WLAN model parameters based on current market values. Some of the cost values (for example, the cost of LoRaWAN gateway) are approximates, but should be representative in a relative sense. The cost values summarized in Tables 2 and 3 are not actual market values because they depend on the time, geolocation, market, and other factors. Similarly, the network performance present in the paper is a general estimate and do not represent the performance of any particular product. For numerical assessment of a DAS with and without ISM and of WiFi-6, an area of $100 \times 100 m^2$ is considered for network deployment with three types of environments. These include moderately open, slightly dense, and moderately dense. The moderately open environment exhibits RF signal
blockages due to big machinery installations in an open area. The slightly dense environment exhibits RF signal blockage due to machinery and 20% of thick walls. The moderately dense environment has RF signal attenuation due to extensive machinery, factory equipment, and up to 60 – 80% of thick walls. Each environment has a level of signal attenuation (shown in Table 4) and affects the effective range of a DA (an AP) for coverage-based network dimensioning. The number of DAs (APs) required for DAS (WLAN) to cover the entire service area is estimated for different environments and is presented in Table 4. For DAS, the range of each DA is estimated considering cellular transmission with maximum allowable path loss (MAPL) of 149 dB. For WLAN, dual band frequencies of 2.4 GHz and 5 GHz transmissions are considered separately with an MAPL of 155 dB. Since the effective range of an antenna is inversely proportional to its operating frequency, the effective range is given by the inequality $R_{900\text{MHz}} > R_{2.4\text{GHz}} > R_{5\text{GHz}}$ for different network types.

For 5 GHz transmission, the signal attenuation is larger compared to 2.4 GHz or DAs; therefore the number of APs required is approximately twice. For a DAS setup with LTE, a single cellular backhaul connection is considered, i.e., $N_{bh} = 1$. For DAS with ISM-band, only one LoRaWAN gateway, i.e., $N_g = 1$ and one RFID transducer, i.e., $N_t = 1$ is considered.

### 6.1 Cost analysis

Using the cost formulation in Sect. 5, CAPEX and OPEX for a network of $100 \times 100m^2$ dimension is estimated for different environment types. As mentioned earlier, some of the costs, such as annual power consumption costs, labor costs, are approximate, but should be representative in real sense. For cost analysis DAS with and without ISM-band technologies are considered. Similarly, WLAN with 2.5 GHz and 5 GHz are considered. Table 5 shows the CAPEX and OPEX values estimated for both DAS and WLAN under three types

### Table 4
Number of DAs (APs) required for $100 \times 100m^2$ service area under different environment estimated

| Environment       | Attenuation from Obstacles (dB) | $N_{DA}$ 900 MHz | $N_{AP}$ 2.4 GHz | $N_{AP}$ 5 GHz |
|-------------------|---------------------------------|------------------|-------------------|-----------------|
| Moderately Open   | 25                              | 3                | 4                 | 8               |
| Slightly Dense    | 30                              | 5                | 7                 | 14              |
| Moderately Dense  | 35                              | 9                | 13                | 24              |

### Table 5
Cost estimation in (SK) for WLAN in 2.4 GHz and 5 GHz, and for DAS with and without ISM-band technologies

| Cost   | Environment          | DAS       | DAS+ ISM | WLAN 2.4 GHz | WLAN 5 GHz |
|--------|----------------------|-----------|----------|--------------|------------|
| CAPEX  | Moderately open      | 24.72     | 29.0     | 19.9         | 24.9       |
|        | Slightly dense       | 31.72     | 35.99    | 23.65        | 32.4       |
|        | Moderately dense     | 45.72     | 50.0     | 31.15        | 46.15      |
| OPEX   | Moderately open      | 1.17      | 1.23     | 0.81         | 1.61       |
|        | Slightly dense       | 1.68      | 1.74     | 1.41         | 2.82       |
|        | Moderately dense     | 2.69      | 2.75     | 2.62         | 5.02       |
of environment. Observe in Table 5, the CAPEX of DAS with and without ISM-band technologies is higher than WLAN. This is due to high cost of RU in DAS when compared to AP in WLAN. Also, note that the addition of ISM-band technologies to the DAS is not very expensive.

For OPEX, two main observations from Table 5 include: (1) The OPEX cost margin between DAS with and without ISM technologies is minimal; thereby the maintenance overhead due to ISM-band technologies is insignificant. (2) The high OPEX for WLAN with 5 GHz transmission is due to deployment of large number of APs (see Table 4). The OPEX estimated in Table 5 is for \( P_f = 0.5 \) and \( \alpha = 0.5 \) for all DAS and WLAN equipment. To understand the impact of \( P_f \) and \( \alpha \) on OPEX, a simulation is performed by varying both the parameters from 0.1 to 0.9 for DAS and WLAN equipment. The results are shown in Fig. 3.

The return on investment for the network deployment is analyzed in terms of NPV (Eq. (1)). To estimate the NPV, two industries, NPP and Oil and gas, are considered in this study. As part of ongoing automation efforts, NPPs are gradually transitioning to automate O&M activities [27] by instrumenting plant assets with wireless sensor technologies. As a result of automation, annual non-safety related equipment maintenance cost decreased by $30,000 per plant [27]. NPPs also moved to less frequent scheduled maintenance of plant assets, resulting in annual average savings of $75,000 per plant [27]. Considering total annual saving of $105,000 per plant as expected cash inflow, and CAPEX and OPEX from wireless network deployment as total cash outflow, the NPV is calculated for 5 years at a discount rate of 10%. In addition, it is also assumed that, every year, the OPEX cost for a wireless network infrastructure is increased by 10%. Based on these assumptions, the calculated NPV values for the NPP industry under different environment, are shown in Table 6. Similarly, the oil and gas industry in 2018 had O&M costs close to $1 trillion across 3000 sites [28]. It is estimated that the automation would reduce total expenses approximately 10% leading to total saving close to $3.3 million per year [28]. For this annual saving, the NPV is calculated for 5 years at a discount rate of 10% for different environment is presented in Table 6. A positive NPV for both the representative industries signifies that the proposed wireless network infrastructure is expected to be profitable.

6.2 Network performance

Network performance of LTE cellular DAS and MU-MIMO OFDMA-based WiFi-6 in terms of throughput and latency (Sect. 4.2) is evaluated using an NS3 simulator. Note

![Fig. 3 OPEX estimation of DAS, DAS+ISM, and WLAN for range of \( P_f \) and \( \alpha \)](image)

\[ \text{Springer} \]
that, industry specific network information in terms of number of wireless devices as well as type of data transmission are not available in open literature. Hence, it is necessary to generalize the scenario of network settings and environment condition without considering a particular industry. Verifying the quality of data transmission under such settings (as shown in Table 4) holds good for any industry and does not limit to NPP or Oil and Gas.

Both DAS (LTE) and WiFi-6 operate over range of bandwidths. LTE supports bandwidth of 1.4 MHz, 3 MHz, 15 MHz, and 20 MHz. The 1.4 MHz and 3 MHz bandwidths are primarily used in narrow-band IoT applications. The WiFi-6 network supports bandwidth of 2 MHz, 20 MHz, 40 MHz, 80 MHz, and 160 MHz. A bandwidth of 2 MHz in the WiFi-6 is also targeted for low-power and low-bandwidth applications. Fig. 4 shows the estimated overall throughput with transmission overheads for LTE and WiFi-6 at their respective supported bandwidths. Note that, throughput are calculated using (Eq. (2)) for

| Industry | Environment  | DAS  | DAS+ ISM | WLAN 2.4 GHz | WLAN 5 GHz |
|----------|--------------|------|----------|--------------|------------|
| NPP      | Moderately Open | 0.407 | 0.402    | 0.414        | 0.405      |
|          | Slightly Dense | 0.398 | 0.393    | 0.407        | 0.391      |
|          | Moderately Dense | 0.379 | 0.374    | 0.394        | 0.367      |
| Oil & Gas| Moderately Open | 13.869 | 13.864   | 13.875       | 13.867     |
|          | Slightly Dense | 13.860 | 13.854   | 13.869       | 13.853     |
|          | Moderately Dense | 13.840 | 13.836   | 13.855       | 13.829     |

**Table 6** NPV in ($M) for different industrial deployments

**Fig. 4** Throughput per DA in LTE-DAS and AP in WiFi-6 for different bandwidths
QPSK, 64 QAM, and 256 QAM modulations with $2 \times 2$ MIMO and for a coding rate of 5/6. For a 100 MHz bandwidth, LTE achieves maximum throughput up to 800 Mbps, whereas for 160 MHz WiFi-6 achieves throughput up to 1.2 Gbps. It is to be noted that, at the bandwidth of 80 MHz, LTE achieves higher throughput as compared to WiFi-6 due to less signaling overhead and interference. WiFi-6 can support an even higher data rate when associated bandwidth is 160 MHz with 1024-QAM modulation.

Figure 5 illustrates achievable spectral efficiency for the range of bandwidths supported by both DAS and WiFi-6. WiFi-6 achieves relatively lower spectral efficiency compared to LTE due to the fact that, the Request to Send and Clear to Send mechanisms in WiFi-6 add to the overhead in data transmission. The lowest allowable bandwidth of 2 MHz in WiFi-6 has significantly large spectral efficiency since it can accommodate more users efficiently along with supporting other wireless technologies such as BLE in that bandwidth.

The network performance of DAS and WiFi-6 for different data traffics is performed using an NS3 simulator. These include, M2M communication (e.g., sensor data), RT video (e.g., surveillance), and HD video. To determine the network throughput and latency for three data types, a network of 50 stationary active user nodes is simulated in NS3 simulator. DAS with LTE is emulated in NS3 [4] using an LTE-EPC module with data rate of 100 Gbps, in which evolved nodeBs (eNBs) are considered as DAs. The downlink and uplink E-UTRA Absolute Radio Frequency Channel Number are set to 3500 and 21500, respectively. The eNBs are uniformly distributed with the total transmission power, $P_T$ Watts. The transmission power of each eNBs is $P_T/N_{DA}$ Watts. The simulation settings of NS3 is detailed in Table 7. The total simulation run time is kept for 30 seconds with all the active nodes transmitting the same type of data. Depending on the data type, the modulation and coding index value is varied along with the channel bandwidth. The network

![Fig. 5 Spectral efficiency per DA in LTE-DAS and AP in WiFi-6 for different bandwidths](image-url)
The M2M and RT video data transmission met the data rate and latency requirements for both DAS and WiFi-6 networks. Also, the PDR was well below the 2% margin. In the case of HD video, the performance of the DAS does not meet the data rate and latency requirements with a high PDR. While, the WiFi-6 network met the requirements.

The variation in WiFi-6 and DAS network performance at different attenuation levels (20 dB, 30 dB, and 40 dB) for three types of data transmission is presented in Table 9. In this analysis, \( N_{AP} = N_{DA} = 10 \). For all the data transmission types, the network performance decreased as the attenuation level increased. The M2M transmission met the required \( N_{TH} \) and \( E[W] \) requirements for both the networks, while RT Video and HD Video transmissions, failed to meet the requirements irrespective of attenuation levels.

The network performance variation due to \( N_{AP} (N_{DA}) \) for the network attenuation level of 20 dBm is analysed and presented in Table 10. For WiFi-6, \( N_{AP} = \{1,2,5,10,15,20\} \) and for DAS, \( N_{DA} = \{1,2,4,6,8,10\} \) are analysed. The modulation and coding scheme (MCS) value was also changed for the three types of data transmission. The MCS for WiFi-6 can be varied from 1 to 31, whereas for DAS, it is varied from 1 to 15. For both WiFi-6 and DAS, MCS of 1, 5, and 10 were used for M2M, RT Video, and HD Video transmissions, respectively. It can be seen that, WiFi-6 achieves higher latency as opposed to DAS for M2M transmissions whereas for both RT Video and HD Video, WiFi-6 achieves QoS close to the required limits.

### Table 7 NS3 simulation settings for DAS and WiFi-6

| Parameter          | DAS-LTE      | WiFi-6       |
|--------------------|--------------|--------------|
| Tx power, \( P_T \) | 25 dBm       | 22 dBm       |
| Frequency band     | 900 MHz      | 5 GHz        |
| Maximum bandwidth  | 20 MHz       | 160 MHz      |
| Modulation         | 16,64,256-QAM| 16,64,512-QAM|
| Payload size       | 1472 Bytes   | 1472 Bytes   |
| Path loss model    | Log-distance Propagation | Log-distance Propagation |
| Reference loss     | 91.53 dB     | 107.72 dB    |
| Reference distance | 1 km         | 1 km         |
| \( N_{DA}(N_{AP}) \) | 9            | 24           |
| #Nodes             | 50           | 50           |

### Table 8 NS3 simulation based network performance

| Data traffic | Required data rate (Kbps) | Required latency (ms) | Network | Throughput (Kbps) | Latency (ms) | PDR (%) |
|--------------|---------------------------|-----------------------|---------|------------------|--------------|---------|
| M2M          | 100                       | <15                   | WiFi-6  | 98.63            | 3.4          | 0.28    |
|              |                           |                       | DAS     | 98.32            | 13.07        | 0.59    |
| RT           | 1500                      | <100                  | WiFi-6  | 1496.47          | 69.91        | 1.26    |
| Video        |                           |                       | DAS     | 1493.48          | 79.06        | 1.87    |
| HD           | 5e3                       | <75                   | WiFi-6  | 4.83e3           | 66.3         | 3.21    |
| Video        |                           |                       | DAS     | 3.04e3           | 104.4        | 39.1    |
The comparison between two networks (Tables 9 and 10) also ascertain our claim "one-size-fits-all" solution is difficult to achieve in industrial wireless infrastructure to meet required QoS for all the applications. Hence, the coexistence of multiple wireless technologies in an industrial setup is crucial to achieve seamless automation.

### Table 9 Performance variation in WiFi-6 and DAS networks in different environments

| Data traffic | Attenuation (dB) | WiFi-6 | | DAS | |
|--------------|-----------------|--------|--------|--------|
|              |                 | $N_{TH}$ | $E[W]$ | PDR (%) | $N_{TH}$ | $E[W]$ | PDR (%) |
| M2M          | 20              | 98.25   | 9.81   | 0.66    | 97.94    | 3.13   | 0.09    |
|              | 30              | 98.18   | 0.14   | 0.07    | 97.87    | 3.12   | 0.09    |
|              | 40              | 98.07   | 1.61   | 0.07    | 97.84    | 3.12   | 0.09    |
| RT           | 20              | 1088.29 | 224.5  | 2.74    | 932.43   | 136.7  | 3.78    |
|              | 30              | 701.91  | 5.55   | 5.29    | 923.11   | 149.8  | 6.82    |
| Video        | 40              | 698.67  | 5.60   | 5.33    | 97.84    | 3.12   | 0.09    |
| HD           | 20              | 1828.68 | 772.0  | 6.34    | 1637.29  | 117.0  | 6.72    |
|              | 30              | 852.56  | 147.60 | 8.36    | 1384.06  | 135.80 | 9.72    |

### Table 10 Performance variation in WiFi-6 and DAS-LTE networks with number of APs ($N_{AP}$) and number of DAs ($N_{DA}$)

| Data traffic | WiFi-6 | | DAS | |
|--------------|--------|--------|--------|
|              | $N_{AP}$ | $N_{TH}$ | $E[W]$ | PDR (%) | $N_{DA}$ | $N_{TH}$ | $E[W]$ | PDR (%) |
| M2M          | 1      | 97.93   | 49.4   | 0.92    | 1        | 98.87   | 6.3    | 0.04    |
|              | 2      | 98.04   | 26.70  | 0.92    | 2        | 98.89   | 4.7    | 0.02    |
|              | 5      | 98.21   | 18.30  | 0.92    | 4        | 98.28   | 4.4    | 0.64    |
|              | 10     | 98.25   | 9.81   | 0.66    | 6        | 98.36   | 3.3    | 0.55    |
|              | 15     | 98.49   | 8.18   | 0.42    | 8        | 97.88   | 3.0    | 1.04    |
|              | 20     | 98.69   | 6.50   | 0.22    | 10       | 97.94   | 3.1    | 0.09    |
| RT           | 1      | 210.02  | 645.4  | 9.56    | 1        | 427.51  | 244.6  | 7.14    |
|              | 2      | 292.53  | 739.9  | 8.04    | 2        | 473.68  | 270.0  | 6.84    |
|              | 5      | 647.36  | 596.9  | 5.68    | 4        | 585.01  | 246.9  | 6.09    |
| Video        | 10     | 1088.29 | 224.5  | 2.74    | 6        | 757.16  | 172.3  | 4.94    |
|              | 15     | 1206.67 | 131.8  | 1.95    | 8        | 855.29  | 147.6  | 4.29    |
|              | 20     | 1311.01 | 89.6   | 1.25    | 10       | 932.43  | 136.7  | 3.78    |
| HD           | 1      | 124.62  | 670.0  | 9.75    | 1        | 428.66  | 254.9  | 9.14    |
|              | 2      | 457.43  | 909.9  | 9.08    | 2        | 474.36  | 276.3  | 9.05    |
|              | 5      | 1321.60 | 842.5  | 7.35    | 4        | 879.64  | 263.0  | 8.24    |
| Video        | 10     | 1828.68 | 772.0  | 6.34    | 6        | 1029.12 | 218.6  | 7.94    |
|              | 15     | 2740.66 | 686.6  | 4.51    | 8        | 1204.07 | 170.2  | 7.59    |
|              | 20     | 3079.62 | 588.6  | 3.83    | 10       | 1637.29 | 117.0  | 6.72    |
6.3 Model’s capability discussion

The simulation results supporting the TEA framework of the proposed multi-band network and the TEA framework under different scenarios lays the groundwork for developing the next generation of wireless network infrastructure for industrial automation. Particularly, this paper describes which wireless technology best suits required applications considering power, distance, and bandwidth. The proposed network is adaptable to variety of applications with different data type transmission requirements. The NS3 analysis provides bounds on network performance. Over time, the network is expected to evolve as new applications are rolled out. To ensure network flexibility, following recommendations can be considered (1) add DAS structure only to a certain section of the service area, (2) deploy 2.4 GHz transmission at the cell edge and 5 GHz transmission close to the cell, (3) deploy a combination of both DAS and WLAN in capacity and coverage limited sections of a service area, and (4) adopt advanced spectrum sharing technologies with heterogeneous network for efficient, high throughput, and energy saving data transmissions.

7 Conclusions and future work

A practical multi-band heterogeneous wireless network is proposed for the industrial automation using DAS and WLAN as the main backend network topology. The TEA analysis of the proposed network is performed by taking into consideration both economical aspects (CAPEX, OPEX, and NPV) and technical aspects (network throughput and latency). Economic evaluation shows that the WLAN requires a significant number of APs to cover the required service area. However, the cost for DAS structures is high due to high RU cost. In addition, both CAPEX and OPEX are directly dependent on the number of RUs in the network. Finally, network performance is evaluated using an NS3 simulation for DAS and WiFi-6 deployment considering three types of data transmissions. For low-bitrate (<1Mbps) applications, the network achieves required performance with an estimated number of $N_{DA}$ for DAS and $N_{AP}$ for WLAN. For higher-bitrate applications, the number of APs required is high to meet the user QoS requirements. The proposed multi-band network and the TEA framework presented here along with simulation results for different scenarios will be useful to understand the next generation of wireless network infrastructure for industrial automation. Particularly, this paper describes which wireless technology best suits required applications.

As part of path forward, DAS with ISM-band technologies will be tested. The resource allocation and throughput maximization challenges will be studied to meet latency and QoS requirements for delay sensitive industrial applications.

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Declarations

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References

1. Jain, S., & Chandrasekaran, K. (2020). Industrial automation using internet of things. In Security and privacy issues in sensor networks and IoT (pp. 28–64). IGI Global.
2. Khorov, E., Kiryanov, A., Lyakhov, A., & Bianchi, G. (2018). A Tutorial on IEEE 802.11 ax High Efficiency WLANs. IEEE Communication Surveys & Tutorials, 21(1), 197–216.
3. B. Barker. A Wireless Eye in Nuclear Plants. [Online]. Available: EPRI Journal, http://eprijournal.com/a-wireless-eye-in-nuclear-plants
4. K. Manjunatha and V. Agarwal, “ISM band Integrated Distributed Antenna Systems for Industry 4.0: A Techno-Economic Analysis,” In 2020 IEEE Global Communications Conference. IEEE, 2020.
5. Christin, D., Mogre, P. S., & Hollick, M. (2010). Survey on Wireless Sensor Network Technologies for Industrial Automation: The Security and Quality of Service Perspectives. Future Internet, 2(2), 96–125.
6. H. Trsek, “Isochronous Wireless Network for Industrial Automation,” In Isochronous Wireless Network for Real-time Communication in Industrial Automation. Springer, 2016, pp. 53–67.
7. Holfeld, B., Wieruch, D., Wirth, T., Thiele, L., Ashraf, S. A., Huschke, J., et al. (2016). Wireless Communication for Factory Automation: An Opportunity for LTE and 5G Systems. IEEE Communication Magazine, 54(6), 36–43.
8. Gedel, I. A., & Nwulu, N. I. (2021). Low Latency 5G Distributed Wireless Network Architecture: A Techno-Economic Comparison. Inventions, 6(1), 11.
9. Alsharif, M. H., Kannadasan, R., Jahid, A., Albreem, M. A., Nebhen, J., & Choi, B. J. (2021). Long-Term Techno-Economic Analysis of Sustainable and Zero Grid Cellular Base Station. IEEE Access, 9, 54–159.
10. Jahid, A., Hossain, M. S., Monju, M. K. H., Rahman, M. F., & Hossain, M. F. (2020). Techno-Economic and Energy Efficiency Analysis of Optimal Power Supply Solutions for Green Cellular Base Stations. IEEE Access, 8(43), 776.
11. Ghazisaidi, N., & Maier, M. (2009). “Fiber-Wireless (FiWi) Networks: A Comparative Techno-Economic Analysis of EPON and WiMAX,” In IEEE GLOBECOM. IEEE, pp. 1–6.
12. V. Krizanovic, D. Zagar, and K. Gregic, “Techno-Economic Analyses of Wireline and Wireless Broadband Access Networks Deployment in Croatian Rural Areas,” In Proceedings of the 11th Int. Conf. on Telecommun. IEEE, 2011, pp. 265–272.
13. T. Smura, Competitive Potential of WiMAX in the Broadband Access Market: a Techno-Economic Analysis. In Proceedings of ITS, 2005.
14. Benseny, J. (2021). Local wireless access provision for rural pen-etration and urban diversification: A Techno-Economic Analysis. Department of Communications and Networking, PhD Dissertation, Aalto University.
15. Sung, K. W., Zander, J., et al. (2013). High Capacity Indoor and Hotspot Wireless Systems in Shared Spectrum: A Techno-Economic Analysis. IEEE Communication Magazine, 51(12), 102–109.
16. Frias, Z., & Pérez, J. (2012). Techno-Economic Analysis of Femtocell Deployment in Long-Term Evolution Networks. EURASIP Journal of on Wireless Communication and Networking, 1, 288.
17. Kamboh, U. R., Yang, Q., Qin, M., & Rauf, S. (2017). “A Techno-Economic Cost Analysis of Heterogeneous Wireless Network.” In IEEE 2nd Advanced Information Technology, Electronic and Automation Control Conference (IAEAC). IEEE, pp. 1645–1650.
18. C. Bouras, V. Kokkinos, A. Kollia, and A. Papazois, “Techno-Economic Analysis of Ultra-Dense and DAS Deployments in Mobile 5G,” In Int. Symp. on Wireless Commun. Systems (ISWCS). IEEE, 2015, pp. 241–245.
19. SOLiD. Alliance Multi-Operator DAS 5W Mid-Power Remote Optic Unit. [Online]. Available: https://solid.com.wordpress/wp-content/uploads/SOLiD-Data-Sheet-ALLIANCE-5W-Remote-Unit-MROU-v2.7.pdf
20. RF Globalnet, “Distributed Antenna System (DAS) for IoT, Cellular, and Other Wireless Applications,” Website: https://www.rfglobalnet.com/doc/distributed-antenna-system-das-for-iot-cellular-and-other-wireless-applications-0001, Tech. Rep., 2017.
21. Kleinrock, L. (1976). *Queueing Systems volume 2: Computer applications* (Vol. 66). New York: Wiley.
22. Z. Zeeshan, “Techno-Economic Analysis of Wireless Indoor Solutions,” 2011, available at: http://www.diva-portal.org/smash/record.jsf?pid=diva2%3A432577&dswid=8368.
23. Winncom. Winncom Products. [Online]. Available: https://www.winncom.com/do/products/f-388/distributed-antenna-systems
24. LORIOT. LoRa Gateways and Concentrators. [Online]. Available: https://www.loriot.io/lora-gateways
25. JADAK. ThingMagic Elara. [Online]. Available: https://www.jadaktech.com/products/thingmagic-rfid/
26. Cisco. Cisco Catalyst 9115 Series Wi-Fi 6 Access Points. [Online]. Available: https://www.secureitstore.com/C9115.asp
27. S. Sarah, “New EPRI Tool Enables Nuclear Plants to Save Millions in Maintenance Costs,” available at: https://eprijournal.com/new-epri-tool-enables-nuclear-plants-to-save-millions-in-maintenance-costs/.
28. Rystad Energy. Oil Industry can Save $100 Billion on Digitalization. Available at: https://www.rystadenergy.com/newsevents/news/press-releases/oil-industry-can-save-100-billion-on-digitalization/.

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