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ORIGINAL RESEARCH

Distributed remote antenna unit with selection-based of (RoF-IoT) paradigm: Performance improvement

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Abstract

Mixing the wireless medium with fiber optics can form a new communication system called a radio-over-fiber (RoF) network; it is a promising solution that can provide high bandwidth and a reliable connection between numerous sensors in wireless sensor networks (WSN) and the central office (base station) within a particular area. This paper first design and discusses new paradigms of fire detection in the IoT environment using RoF technology. Second, this paper covers the distribution of remote antenna unit (DRAU) architecture within RoF-IoT. Finally, best remote antennas unit selection (BRAUS) of distributed RAUs architecture protocols utilizing new selection metrics is proposed. Two important metrics have been analysed and mathematically modelled, outage probability and bandwidth efficiency, respectively. Both metrics have been analysed as a function of the distance, number of RAUs, fiber optic attenuation, and path loss factor. Based on the simulation and numerical analysis, the outage probability of proposed protocols is reduced by 65% compared to recent work; in addition, the bandwidth efficiency of the proposed protocol is increased by 34% compared to recent work.

1 | INTRODUCTION

In the 1990s, the fiber-wireless (FiWi) network, also known as a mixed optical-wireless network or a mixed wireless-optical broadband access network, is presented as a cost-effective "last mile" Internet access solution [1, 2]. Over the last two decades, the FiWi network, which combines a network of the optical fiber with a wireless access network, was appealed a lot of academic attention and experienced tremendous growth in its applications, which range from multi-media communications to tele-presence to disaster relief [3–8].

The coming internet of things (IoT) technologies frontier arouses colossal interest. Basically, its deployment possible rely on one of the existing wireless communication systems, where numerous efforts have been made to adjust new IoT applications to numerous current wireless technologies, with current plans for new mobile systems developed which can be used in the Industry 5.0 era [9]. Combining wireless and fiber optic networks appears to be a feasible approach to meet the increasing data traffic demand from mobile applications. To date, no one standard has been able to satisfy all IoT application requirements in terms of complexity as well as cost; then power consumption and transmission speed; or the so-called Smart City. [10]. A novel IoT networking scenario utilizes optical fiber-based wired networks directly connected to IoT devices. It is must be to overcome inherent wireless network constraints, such as, Passive optical networks (PONs) may be a solution with long reach and high data rates. Electrical-to-optical conversions can be power consuming [11] and expensive for some IoT devices, and such physical connectivity (PHY) may be overkill for most IoT data rate necessities. Therefore, we need to bridge the gap for low data rate long distance passive optical systems [12].

1.1 | Motivation

The RoF network has gathered a lot of attention of researchers in recent years. However, so far, no works have considered the distributed antennas scenarios integrated with wireless sensors networks; also no works have considered distributed remote antennas scenarios in IoT. In addition, no work used remote

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antennas unit selection. The contribution of this work can be summarized as follow:

1. This paper, for the first time, proposed new design of the RoF-IoT paradigm for early fire detection as case study using camera sensors and other possible sensors, in the proposed design, sensors gathered the information from the environment and gathered information transmitted to the particular section to take suitable action/decision.
2. Best remote antennas unit selection (BRAUS) was proposed, where selection criteria is based on number of the RAUs, number of master nodes, and distance over various links in the RoF-IoT paradigm.
3. The outage probability of the proposed protocol, BRAUS, has been mathematically modelled and driven, where the outage probability of proposed protocols reduced by 65% compared to recent work.
4. Also and for the first time, the bandwidth efficiency has been studied, mathematically modelled, driven and analysis of the BRAUS, then it proven that the bandwidth efficiency of the proposed protocol is increased by 34% compared to recent work.

The rest of the paper is organized as follows. Proposed system structure and their moulding are highlighted in Section 2 which include radio over fiber in IoT paradigms as well as communication scenario. In Section 3, we discusses the propagation mathematical model and their characteristic for both radio signals over wireless medium and optical signal over fiber optics. Section 4 provides outage probability formulation including the proposed protocol driven in terms of distance, path-loss, SNR, antennas gain, attenuation; in addition, the bandwidth efficiency has been driven with integrating the proposed protocol. Section 5 shows the validation of the proposed protocol against the proposed published works. Finally, Section 7 draws the conclusion and future works.

1.2 | Related work

In the scope of the H2020 FUTEBOL project, a testbed of Internet-of-Things (IoT) for environmental monitoring based on RoF is being developed and studied in the [13]. Furthermore, a new methodology based on real-world scenarios is used to measure the influence of RoF on network performance. A mobile edge computing (MEC) assisted-based Fiber–Wireless (FiWi) LTE enhanced HetNets is proposed and designed in [14], This makes it possible for traditional (remote) cloud with MEC servers to be colocated and collaborated. To bridge the gap between the rising needs for computation-intensive, delay-sensitive operations, as a result of developing 5G applications. A distributed cooperative offloading technique with the goal of decreasing the average reaction time for mobile users after presenting our an analytical framework to evalaute energy-delay performance for the IoT over fiber (IoToF) that is totally rely on passive optical key along with dark fiber is investigated in [15]. Then, implemented and characterized a prototype physical connectivity (PHY) rely on fiber Bragg grating (FBG) low-cost acousto-optic modulation is proposed and designed. In the terms of data rate and reach for niche applications, the proposed architecture show superior performance to the existing works Sigfox or LoRa.

Two Radio over Fiber approaches is surveyed and presented in [16] which are Radio Frequency over Fiber (RFoF) and intermediate Frequency over Fiber (IFoF), both transmissions approaches well-suited with the essential new services of the broadband and both play a vital role in the design of next-generation integrated optical–wireless networks, for example, 5G and Satcom networks, by integrating new features on RAU to enhance physical dimensions, using a micro-electronic layout over nonmetric technologies. IoT development of the roadmap from 5G toward 6G and the potency of optic fiber and RoF technologies is revived and studied in [17]. Further, rapidly increasing of the radio over fiber marketplace in addition to technologies linked to IoT-RoF convergence is presented including discussing of the recent outstanding researches in numerous scopes. It is followed the, they discussed the challenges ahead for the future RoF supported 6G IoT systems and the emerging technology solutions.

A Mixed FSO and fiber using AF backhauling methods is analytical presented in [18], the effects of RF interference-co-channel, pointing errors, and nonlinearities of the modulator are demonstrated and discussed. Asymptotic expression is derived for the outage probability, the average bit-error rate, and the cumulative distribution function of the link capacity. The results shows that in the term of the capacity reached 50% higher using mm-Wave compared to the existing work.

Power-over-fiber (PoF) is consider as recent and advance solution for the future 6 and 5G networks in using radio signals is proposed and analyzed in [19]. Followed by the implementing an experimentally of the Radio-over-fiber broadcasting over single mode fiber (SMF) over link vary from 100 m up to 10 km with injected PoF signals limited to 2 W. Using PoF technologies can optically forwarded the power to the distant device/systems and IoT technologies rely on RoF links is also taken into consideration. To date, few works have studied, analysis and formulated the outage probability in the RoF-IoT paradigm.

A multiuser mixed RF/FSO relays methods as viable means of improving the stringent requirements with considering the small-cell system design is presented in [20]. Furthermore, outage probability of link for the hybrid RF/FSO approach with taking into account the effect of pointing errors in the FSO links is studied and investigated. The results show that the hybrid RF/FSO methods can improve the communication system in the real life. In the [21] a hybrids mm-Wave-RoF with AF methods performance are investigated for 5G networks. Nonlinearities of the Optical fiber, nonlinearities of the optical modulator, and RF co-channel interference effect on the performance of the mixed mm-Wave RoF paradigms are studied and analyzed. The outage probability and the average BER of the whole link is expressed and mathematically modelled in a simplified closed form expressions. Comparison of the state-of-arts is given in Table 1.

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TABLE 1 Comparison state of arts

Highlight	Metrics	Protocols/methods	Pub. year [Ref. No.]
• Proven of the appropriateness of RoF technologies for IoT eco-friendly systems. • Measuring the impact of RoF systems on performance of the network is validated and checked.	• RSSI • Packet success ratio • Average packet delay	H2020 Futebol project	2018 [13]
• FiWi architecture is introduced which can enhance HetNets considering multi-access computing (MEC) servers. • Estimating the energy as well as the delay analytical with taking into account the MEC. • Offloading strategy with distributed cooperative is utilized to reduce the average response time for the mobiles users.	• Energy consumption • Average response time of the server • Offloading probability	Multi-access computing (MEC) enabled Fiber–Wireless (FiWi) LTE enhanced HetNets	2019 [14]
• Developing of new modulation scheme for the low-cost FBG based acousto-optic compatible with RoF in the IoT paradigm. • Multiplexing flexibility with the FBG technologies is studies • Demonstration that IoT-RoF not expected to replace existing optical networks nor wireless networks.	• Bit error rate	No specific protocol is defined	2019 [15]
• A review of two Radio over Fiber approaches is presented. • Radio-Frequencies-over-Fiber (RFoF) and intermediate-Frequencies-over-Fiber (IFoF) are two transmission approaches.	• RFoF • IFoF	Review paper	2020 [16]
• Challenges in the future. • Complex model design. • High efficient training. • Heterogeneous data computation.	• 6G IoT systems Roadmap with RoF networks	Review paper	2020 [17]
• Design and analysis the FSO backhauling by including link of the fiber optic. • Interference causing by Co-channels, errors of the pointing, and FSO links scintillation are considered explicitly.FSO Nonlinearity effect with fiber relay node has been considered for the proposed systems.	• Outage probability • Bit error rate	FSO/fiber amplify-and-forward backhauling	2017 [18]
• Study the challenges of the Radio over fiber using light system for various application. • Design RoF systems parameters and statement the main regulating factors.	• Error Vector Magnitude (EVM)	Power-over-fiber (PoF)	2021 [19]
• Hybrid RF/FSO relay approach to achieve optical-wireless convergence in dual-hop network systems. • Studied and analysis of the outage probability from the source to destination for the mixed RF/FSO approach with taking into account the pointing errors of the FSO links.	• Outage probability	Multiuser mixed radio-frequency/free-space optical (RF/FSO) relay schemes	2017 [20]
• Nonlinearity effects of the optical fiber, nonlinearity of the modulator of the optical, and radio-frequency (RF) co-channel interference is studied on the performance of the mixed mmWave RoF networks. • Formulating and simplification of the end-to-end bit error rate and outage probability in the existing of the nonlinearities.	• Outage probability • Bit-error rate (BER)	Mixed millimeter-wave and radio-over-fiber (mmWave RoF) amplify-and-forward (AF) systems	2018 [21]
• Design early fire-detection system based on the RoF-IoT • Analysis and mathematically modelling the outage probability of the BRAUS protocol. • Analysis and mathematically modelling of the bandwidth efficiency of the BRAUS protocol.	• Outage probability • Bandwidth efficiency	Best remote antennas unit selection (BRAUS) of distributed RAUs architecture protocols	Proposed work

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This paper focus on the outage probability and bandwidth efficiency, however, few works, in **[18]** **[20-21]**, have considered the outage probability, and the limitation of those works are summarized

1. All the works in the literature use single fiber optics for transmission/reception of the data from the RAU to central office, which almost arises the concept of single point of failure (SPOF), where if the fiber medium fails to transfer the data, the whole system is down.
2. All the works in the literature used single antennas unit to accommodate large number of connection will cause serious interference problem as it is demonstrated in [19] and [20], because there will be several sensor willing to communication over RAU which rises the interference.
3. All the suggested communication scenarios of RoF-IoT were based on distributed sensors systems instead of cluster-based scenario, non-cluster-based scenario make difficulties of regulating transmission between sensors and RAU.
4. Finally, one of the important metrics has not been analyzed and never studied in the literature, nor mathematically neither simulation, is the bandwidth efficiency, bandwidth efficiency represent number of slots/channels required to transmit single packets.

2 | PROPOSED SYSTEM STRUCTURE AND MODELLING

2.1 | Radio over fiber in IoT

One of the problem of the early fire-detection in the forest, dangers area (such as power plant, distribution electricity zone, so on) is difficult to be installed or to be reached due nature of area. Thus, and for this reason, we consider in our design the early-fire detection system.

For the dense wireless sensors network, there is an option to reach sensors that distributed in heavy terrain or industrial environments through distributing RAUs in particular area to be totally covered by radio signal which can be called as distributed antenna systems (DAS) in the RoF paradigms. The proposed structure in our scenario, comprised from small master nodes (MN) distributed in the heavy terrain or industrial environments to provide good coverage radio signal over a specific area, then sensors have two possible connection, one directly to the RAU, and other to RAU through master node. The details of the communication will be described latterly in the section 2.2.

In this work, we proposed distributed-RAUs in IoT paradigms with RoF technology to provide higher bandwidth, long reach, integrity of the signal, and securing-data. The envisioned or proposed paradigms are shown in Figure 1, where it is comprised of four regions, each region have specific job and it is part of the whole IoT system. In this work, an early fire detection and remedy system is taken into consideration. We can summarize the proposed paradigm as follow:

1. **Region 1,** early fire detection (sensing regional/camera-based sensors): in this region sensors (sensors can be cameras, smoke detectors, CO detector etc.) located in the particular region (heavy or unreachable region) which are distributed in the random or regular manner. After sensors collect the data, it is transferred to RAUs or the master node based on the protocol that will be described in the later section. Where, master node had higher ability, larger battery size, and larger size compared to normal sensors. After Master node received what transmitted by the sensors, it is forward the data to the RAU.
2. **Region 2,** Remote antenna unit (RAU) region, in this region data received and converted from the electrical signal to optical signal to be transfer over fiber optic.
3. **Region 3,** base-station or super master node, in this region data received from the fiber optic which already converted from optical to electrical signal. Super master node has two main jobs, first it is process the data and make suitable decision to where the data should be forwarded (it is select suitable department), secondly, it is forward the data to the region four.
4. **Region 4,** in this region, analyzed data is received, then particular department take an action, either fire department, beacon system etc.

2.2 | Proposed communication structure for RoF in IoT paradigm

In this section detail of the proposed communication structure, proposed selection method were inspected and analyzed. The communication model of traditional RoF system in the IoT environment is explained as follows [19, 21]; the traditional communication scenario is comprised of three phases:

1. In the first phase (phase#1), the sensors gathered data from the particular area and then forwarded to the master node.
2. Then, in the second phase (phase#2), the master node forwarded what received from the sensors to the RAU over wireless medium (single RAU).
3. Finally, in the third phase, RAU drops the data on the fiber optics to be submitted to the base-station (remote central office). The traditional communication of radio of fiber is shown in Figure 2b.

The proposed structure is comprised of three phases and multiple RAUs which are distributed uniformly in triangular way, triangular RAU distribution is reachable by sensors and most of the master nodes, which is shown in Figure 2a.

The communication scenario can be described as follow:

1. In the first phase (phase#1), the sensors collected the data (either regular data or critical data) per period of time from the surrounding area (in this paper maximum area can be covered by the sensors is 10 m), then collected data transmitted over wireless medium with two options:

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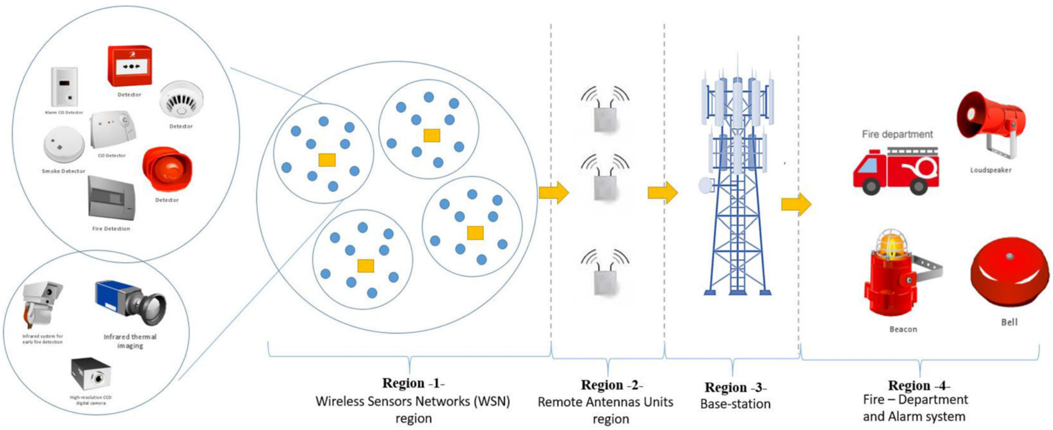

FIGURE 1 Envisioned distributed RAU of the RoF in IoT paradigm

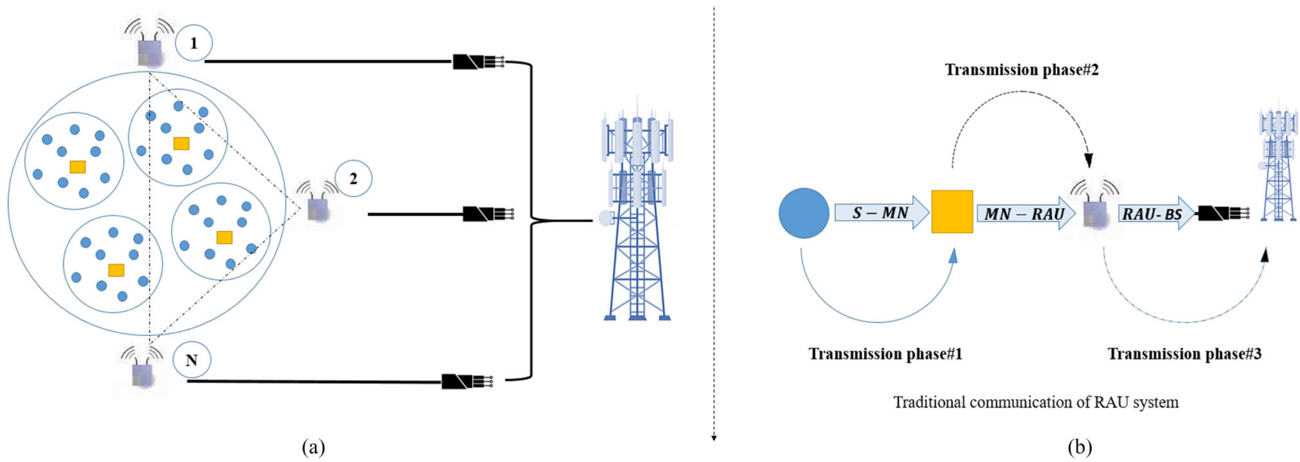

FIGURE 2 Communication structure of traditional RoF

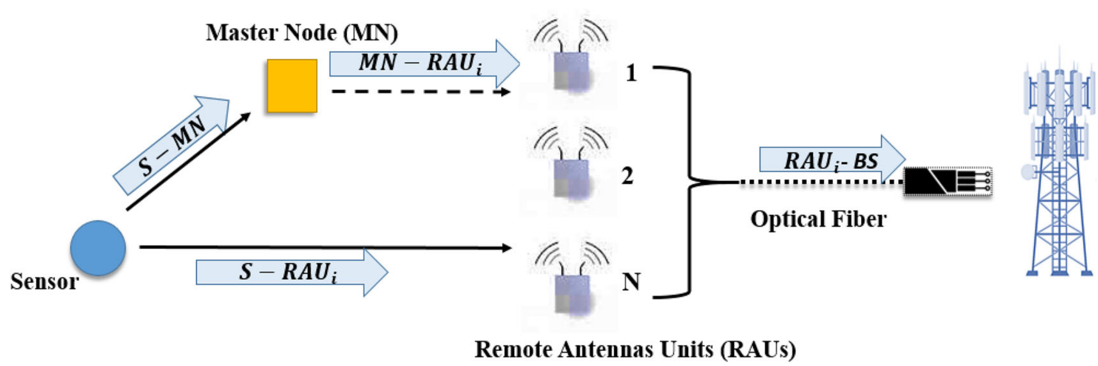

FIGURE 3 Best RAU selection-based protocol: there are two possible paths; first path over $S - RAU$ and $RAU - BS$ links, then second path S-MN, MN-RAUi and RAUi-BS

2. First option (first-path): gathered data transmitted to the nearest RAU and selection based on the proposed metric that is consider wireless medium and optical fiber factors. After selection takes place, the gathered data transmitted over best RAU and RAU drops the information on the fiber optic to be forwarded to the base-station or central office unit.
3. Second option (second-path) : if the best RAU is not available within the range of the sensor, then the gathered data travel over second possible path, the sensor transmits the

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TABLE 2 Simulation parameters

Symbol	Definition	Value
’$_{i,j}$	Antennas gain over $i-j$ link	3
R_o	Transmission rate to bandwidth over $i-j$ link	0.5
$d_{i,j}$	Distance over $i-j$ link (within sensors region)	5–50 m
α	Path-loss factor	2–6
SNR	Signal to noise ratio	0–50 dB
OSNR	Optical signal to noise ratio	0–50 dB
L_{total}	Total length of the optical fiber	0–50 km
γ	Nonlinearity coefficient	1–2
B_{OF}	Optical fiber bandwidth	32 GHz
R	Number for remote antenna unit	5–25

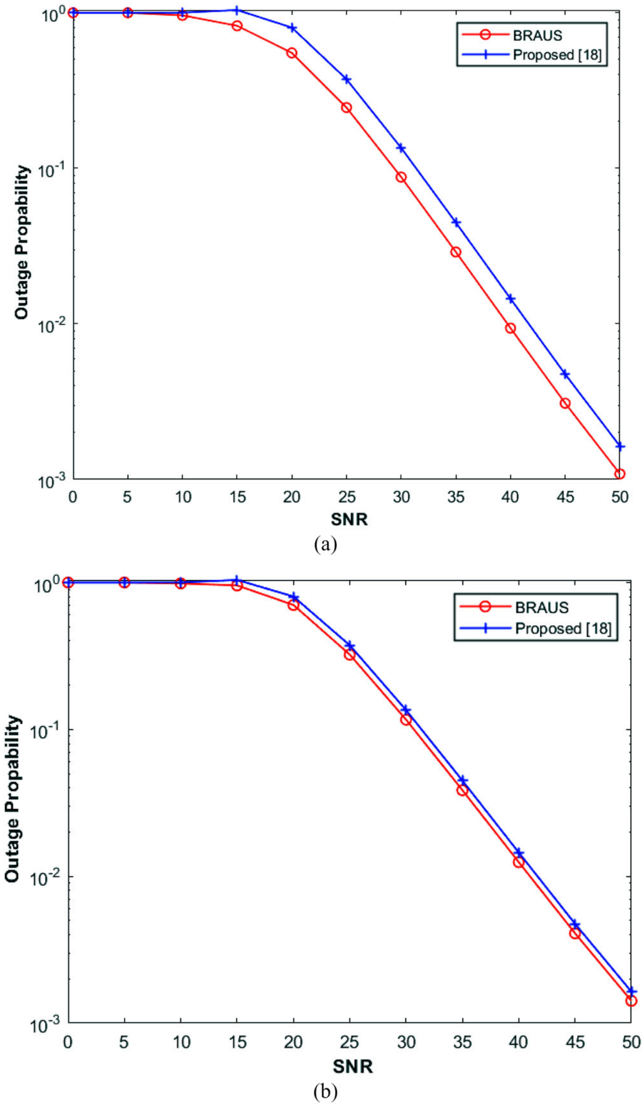

FIGURE 4 Outage probability as a function of the SNR; for (a), the number of the RAUs, R, is set to 30; for (b), the number of the RAUs, R, is set to 10

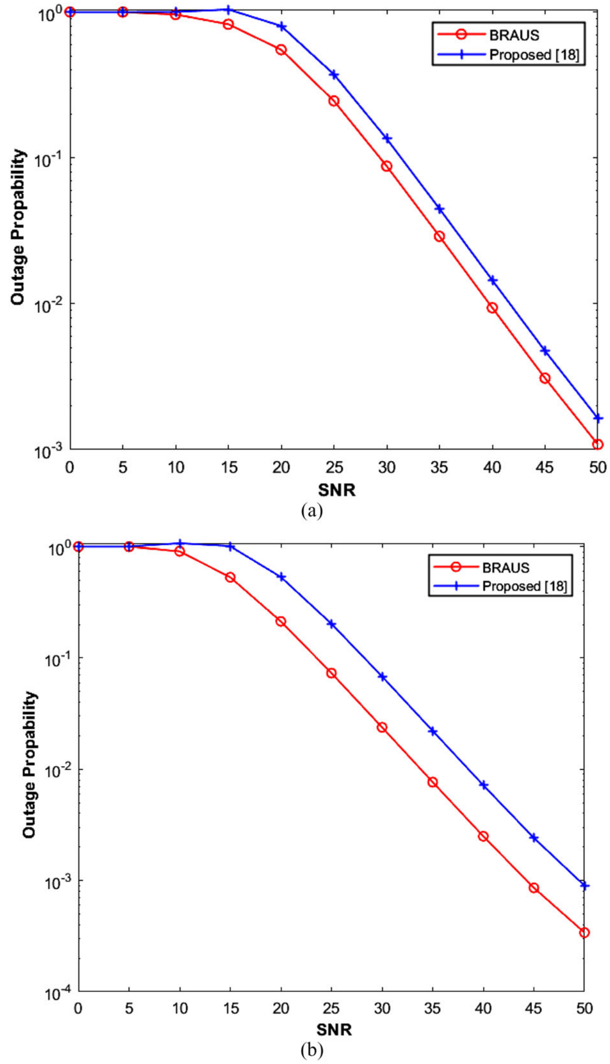

FIGURE 5 Outage probability as a function of the SNR, where pathloss, α, is set to 4. For (a), the threshold value, β_{thd} , is set to $0.5d_{srau}^{-\alpha}$; for (b), the threshold value, β_{thd} , is set to $2d_{srau}^{-\alpha}$

data to master node within transmission range, then master node transmits what is received from the sensor to the RAUs.

4. In the second phase, the nearest master, then at the second phase (phase#2), the master node broadcasted the data to selected RAUs, then, it is followed by the phase three (phase#3), the selected remote antenna unite forwarded the data to MRC, the summed signals are then dropped to the base-station (remote central office).

2.3 | Propagation mathematical model

2.3.1 | Propagation model of the radio channel

In this sub-section, the channel model is analysis and outage probability over the i − j link is described. The signal-to-noise

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ratio ($\gamma_{i,j}$) of the $i-j$ link is given as [22]:

$$\gamma_{i,j} = \left(\frac{P_T}{P_N}\right)\ \rho_{i,j}\ =\ SNR\ \rho_{i,j}\ , \tag{1}$$

in which P_T is the transmission power, P_N represents noise power and $\rho_{i,j}$ represents Gaussian-Complex random variable of the unit variance, accordingly, $\rho_{i,j}$ denoted as an exponential distributed random variable with the mean value, $E\ [\rho_{i,j}]\ = |a_{i,j}|^2\ d_{i,j}^{-\alpha}$, where $E[.]$ denotes expectation and the $d_{i,j}$ is the distance of the $i-j$ link, α represents path-loss factor and values lies between 2 and 6. In what follows, the transmission rate over $i-j$ link can be expressed as [23]:

$$R_{i,j} = B\log_2\left(1 + SNR\left|a_{i,j}\right|^2 \sigma_{i,j}^2\right), \tag{2}$$

where B represents bandwidth of the channel, the outage probability is defined as the probability that the transmission rate is less than or equal the required transmission rate R_o . The outage probability can be expressed as [23]:

$$P_{i,j}^{out} = P\left(R_{i,j}\ \leq R_o\right)\ =\ 1 - \exp\left(-\ \frac{\left(2^{R_o}-1\right)}{SNR}\ \frac{1}{\sigma_{i,j}^2}\right). \tag{3}$$

The successful transmission probability of the $i-j$ link can be expressed as

$$P_{i,j}^{s}\ =\ 1 -\ \ P_{i,j}^{out}\ = \exp\left(-\ \frac{\left(2^{R_o}-1\right)}{SNR}\ \frac{1}{\sigma_{i,j}^2}\right)\ (4)\ . \tag{4}$$

Then, we describe a method to estimate the capacity limit of fiber-optic communication systems (or "fiber channels") based on information theory. In what follows, the transmission rate over $i-j$ link can be expressed as [23, 24]:

$$R_{i,j}\ = B_{OF}\ \log_2\left(1 +\ \ OSNR\right)\ , \tag{5}$$

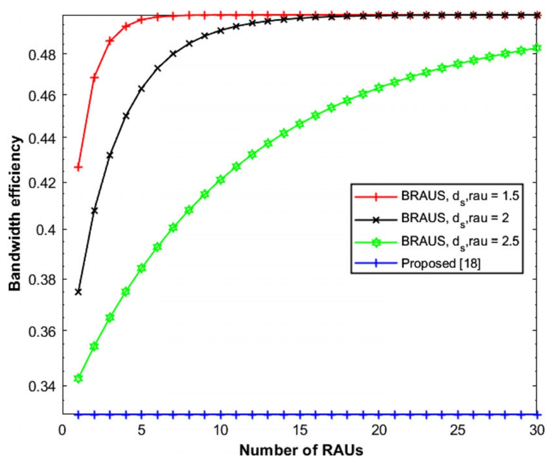

FIGURE 6 Bandwidth efficiency as a function of number of RAUs

where OSNR is the optical signal-to-noise ratio, which can be approximated as [23, 24]:

$$\text{OSNR}\ =\ \frac{R_b}{2B_{ref}}\ \ SNR\ (6)\ , \tag{6}$$

where R_b is the transmission rate and B_{ref} is reference bandwidth.

2.4 | Out probability of proposed protocol

2.4.1 | Formulation of the best RAU selection-based (BRAUS) protocol

In this sub-section, the proposed protocol, best RAU selection-based (BRAUS) protocol of Radio over Fiber in IoT paradigms (RoF-IoT), is modelled and formulated based on the description given in Figure 3, the outage probability then can be expressed as:

$$\text{P}_{\text{BRAUS}}^{\text{out}} = \underbrace{\text{Path\#1}^{\text{out}}}_{\text{s}\rightarrow\text{rau}\ \&\ \text{rau}\rightarrow\text{bs}} \cup \underbrace{\text{Path\#2}^{\text{out}}}_{\text{s}\rightarrow\text{mn}\ \&\ \text{mn}\rightarrow\text{rau}\&\text{rau}\rightarrow\text{bs}}\ , \tag{7}$$

$$\text{P}_{\text{BRAUS}}^{\text{out}} = \underbrace{\text{Path\#1}^{\text{out}}}_{\text{s}\rightarrow\text{rau}\ \&\ \text{rau}\rightarrow\text{bs}} + \underbrace{\text{Path\#2}^{\text{out}}}_{\text{s}\rightarrow\text{mn}\ \&\ \text{mn}\rightarrow\text{rau}\&\text{rau}\rightarrow\text{bs}}\ , \tag{8}$$

in which, the outage probability of the Path#1 is expressed as

$$\text{Path\#1}^{\text{out}} = \left(P_{s,rau}^{out} + \left(1 - P_{s,rau}^{out}\right) P_{rau,bs}^{out,AF}\right) P_{\beta_{max}}\left(\omega\beta\right), \tag{9}$$

in which $P_{s,rau}^{out}$ and $P_{rau,bs}^{out,AF}$ are the outage probabilities of the $S-RAU$ and $RAU-BS$ links, respectively. In what follows, $P_{rau,bs}^{out,AF}$ is expressed as

$$P_{s,rau}^{out} = 1 - \exp\left(-\frac{\left(2^{R_o}-1\right)}{SNR}\frac{1}{\sigma_{s,rau}^2}\right). \tag{10}$$

$P_{rau,bs}^{out,AF}$ is the amplify-and-forward outage probability, and it is expressed as

$$P_{rau,bs}^{out,AF}\ = 1 - \exp\left(-\frac{1}{\sigma_{s,rau}^2}\left(\frac{\left(2^{R_o}-1\right)}{SNR} - \frac{R_b}{2B_{ref}}\right)\right). \tag{11}$$

$P_{\beta_{max}}(\omega\beta)$ is the probability the $S-RAU$ and $RAU-BS$ path selection, and it is expressed as

$$P\left(\beta_{max} \geq \omega\beta_{thd}\right) = P_{\beta_{max}}\left(\omega\beta_{thd}\right)$$
$$= 1 - \left(1 - \exp\left(-\frac{\beta_{thd}}{\sigma_{s,rau}^2}\frac{L_{total}}{L_{max}}\right)\right)^R. \tag{12}$$

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in which β_{max} is the random variable of the link $S - RAU$, β_{thd} is the threshold distance of the $S - RAU$ link, $\sigma^2_{s,rau}$ is the $d^{-\alpha}_{s,rau}$, ω is $\frac{L_{total}}{L_{max}}$, ratio of the total length of the optical fiber link, L_{total}, to maximum fiber link, L_{max}, R is the number of the remote antennas units. We can conclude from the proposed selection formula the following points; as the number R goes to infinity, the $P_{\beta_{max}}(\omega\beta_{thd})$ approaches to one, it means the chance of finding god RAU for sensor is centrally available, and vice versa. In addition, if the ω is low, the $P_{\beta_{max}}(\omega\beta_{thd})$ is high, because the probability of path selection tend to select the best $S - RAU$ path with minimum fiber optics length.

Then, the outage probability of the second path is given as

$$\text{Path\#2}^{\text{out}} = \left(P^{out}_{s,mn} + \left(1 - P^{out}_{s,mn}\right) P^{out}_{mn,rau} + \left(1 - P^{out}_{mn,rau}\right) P^{out,AF}_{rau,bs} \right) \left(1 - P_{\beta_{max}}(\omega\beta)\right), \quad (13)$$

where $P^{out}_{s,mn}$ and $P^{out}_{mn,rau}$ are the outage probability of the $S - MN$ and $MN - RAU$ links. In what follows, $P^{out}_{s,mn}$ and $P^{out}_{mn,rau}$ are expressed as

$$P^{out}_{s,mn} = 1 - \exp\left(-\frac{\left(2^{R_o} - 1\right)}{SNR} \frac{1}{\sigma^2_{s,mn}}\right), \quad (14)$$

$$P^{out}_{mn,rau} = 1 - \exp\left(-\frac{\left(2^{R_o} - 1\right)}{SNR} \frac{1}{\sigma^2_{mn,rau}}\right). \quad (15)$$

Finally, the outage probability of the proposed protocol is given as

$$\begin{aligned} \text{P}^{\text{out}}_{\text{BRAUS}} = & \underbrace{\left(1 - \exp\left(-\frac{\left(2^{R_o}-1\right)}{SNR}\frac{1}{\sigma^2_{s,rau}}\right)\right)}_{P^{out}_{s,rau}} \underbrace{\left(\exp\left(-\frac{\left(2^{R_o}-1\right)}{SNR}\frac{1}{\sigma^2_{s,rau}}\right)\right)}_{1-P^{out}_{s,rau}} \underbrace{\left(1 - \exp\left(-\frac{1}{\sigma^2_{s,rau}}\left(\frac{\left(2^{R_o}-1\right)}{SNR} - \frac{R_b}{2B_{ref}}\right)\right)\right)}_{P^{out,AF}_{rau,bs}} \underbrace{\left(1 - \left(1 - \exp\left(-\frac{\beta_{thd}}{\sigma^2_{s,rau}}\frac{L_{total}}{L_{max}}\right)\right)^R\right)}_{P_{\beta_{max}}(\omega\beta_{thd})} \\ & + \left[\underbrace{\left(1 - \exp\left(-\frac{\left(2^{R_o}-1\right)}{SNR}\frac{1}{\sigma^2_{s,mn}}\right)\right)}_{P^{out}_{s,mn}} + \underbrace{\left(\exp\left(-\frac{\left(2^{R_o}-1\right)}{SNR}\frac{1}{\sigma^2_{s,mn}}\right)\right)}_{1-P^{out}_{s,mn}} \underbrace{\left(1 - \exp\left(-\frac{\left(2^{R_o}-1\right)}{SNR}\frac{1}{\sigma^2_{mn,rau}}\right)\right)}_{P^{out}_{mn,rau}} + \underbrace{\left(\exp\left(-\frac{\left(2^{R_o}-1\right)}{SNR}\frac{1}{\sigma^2_{mn,rau}}\right)\right)}_{1-P^{out}_{mn,rau}} \right. \\ & \left. \underbrace{1 - \exp\left(-\frac{1}{\sigma^2_{s,rau}}\left(\frac{\left(2^{R_o}-1\right)}{SNR} - \frac{R_b}{2B_{ref}}\right)\right)}_{P^{out,AF}_{rau,bs}} \right] \underbrace{\left(\left(1 - \exp\left(-\frac{\beta_{thd}}{\sigma^2_{s,rau}}\frac{L_{total}}{L_{max}}\right)\right)^R\right)}_{1-P_{\beta_{max}}(\omega\beta_{thd})} \end{aligned} \quad (16)$$

3 | BAND WIDTH EFFICACY OF PROPOSED PROTOCOL

One of the important metric in the communication system is the bandwidth efficiency. Bandwidth efficiency in this paper is defined as the number of channels/slots required to transmit single packet/frame to destination. For example, to transmit a packet/frame over two hops, two channel/slots are required to reach the destination, therefore, bandwidth efficiency for aforementioned case is 0.2 [25–27].

According to our discussion in the previous section, the mathematical model average bandwidth efficiency of the described protocol of the Best RAU Selection (BRAUS) in IoT-RoF Paradigm is given below:

$$BE_{\text{BRAUS}} = \underbrace{\frac{1}{2}P_{\beta_{max}}(\omega\beta_{thd})}_{case\#1} + \underbrace{\frac{1}{3}\overline{P_{\beta_{max}}(\omega\beta_{thd})}}_{case\#2}, \quad (17)$$

$$\begin{aligned} BE_{\text{BRAUS}} &= \underbrace{\frac{1}{2}P_{\beta_{max}}(\omega\beta_{thd})}_{case\#1} + \underbrace{\frac{1}{3}\left(1 - P_{\beta_{max}}(\omega\beta_{thd})\right)}_{case\#2} \\ &= \frac{1}{6} + \frac{1}{3}P_{\beta_{max}}(\omega\beta_{thd}), \end{aligned} \quad (18)$$

in which $P(\emptyset) = f(d_o, d_{srau})$ is the probability of the selecting direct transmission from the sensor to RAU which is given in Equation (12), and best RAU selected. Then, $P(\emptyset)$ is the probability that direct transmission between sensor and RAU is not available, and cannot find best RAU, which is given in (12). We can rewrite (18) as

$$BE_{\text{BRAUS}} = \frac{1}{6} + \frac{1}{3}\left(1 - \left(1 - \exp\left(-\frac{\beta_{thd}}{\sigma^2_{s,rau}}\frac{L_{total}}{L_{max}}\right)\right)^R\right). \quad (19)$$

It is clear from Equation (19), as the $P_{\beta_{max}}(\omega\beta_{thd})$ approaches one, the bandwidth efficiency is 1/2, on the other hand, as the $P_{\beta_{max}}(\omega\beta_{thd})$ approaches zero, the bandwidth efficiency is 1/3. As expected and observed from Equation (19), using direct communication between sensors and RAU can save and improve the bandwidth efficiency. Therefore, using mutli-hop communication in the traditional communication of RoF in IoT is not always preferred. However, direct transmission may not be reliable and multi-hop communication is more reliable.

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4 | RESULTS AND DISCUSSION

In this section, we evaluate the performance of the proposed best RAU selection-based (BRAUS) protocol for RoF in the IoT of the early fire detection scenario via computer simulations. In the simulations, a random topology of the sensors and master nodes is located with area of 4 km × 4 km, and multiple RAUs are distributed within same area (maximum RAU in this paper is 25), where RAUs are connected to central office or base station via fiber optic with maximum length of 25 km. The distances between sensors-RAU link, sensors-master node, Master-RAU, RAU-BS are assumed to be variable in the simulations. The transmission rate of the all links are assumed to be β_o $(b/s/Hz)$, and all links are from the sensors, master nodes to RAU as variable and denoted as d_o. The path-loss exponent is not fixed in this paper. The complete parameters are listed in Table 2.

Figure 4 shows the comparison of outage probability of proposed protocol BRAUS versus [18] as a function of *SNR* with respect to the number of the RAUs. From the figure, we observed the following: The outage probability of the proposed protocol and outage probability of the reference decay with increased SNR. The outage probability of the proposed protocol has better performance (less outage probability) compared to protocol proposed in [18]. As expected, the outage probability is better when the number of the RAUs increased, when we compared Figures 4a and 4b; this is because, as number of the RAUs increased, the probability of the finding best RAUs increased, therefore, outage probability reduced.

Figure 5 shows the comparison of outage probability of proposed protocol BRAUS versus [18] as a function of *SNR* with respect to the threshold value, β_{thd} . From the figure, we observed the following: As expected, the outage probability reduced as the *SNR* goes higher. Again, we noticed that, the proposed protocol had better performance compared to those protocol given the paper [18] because best RAUs are selected and best path is chosen using proposed protocol in this work. We observed that outage probability reduced as the threshold value increased, because larger distance will promise that higher probability of the RAUs fall within the range of the transmitter; therefore, there is chance to find a good path to RAU that can be connected to transmitter and forward the data to the base station.

Figure 6 shows the comparison of bandwidth efficiency of proposed protocol BRAUS versus [18] as a function of number of the RAUs. In this figure, the distance from the sensor to the RAUs, $d_{s,rau}$, has been varied between 1 and 2.5. From the results, as the number of the RUAs increases, the bandwidth efficiency increases as well; that is because as RAUs increased, the probability of finding best or nearest RAUs increased and bandwidth efficiency approached 0.5 as given in Equation (19). We noticed that, as distance between senor and RAUs reduced, the bandwidth efficiency increased, because the protocol will select the dual hop path instead of the triple hop path as shown in Figure 3. Finally, the proposed protocol had better performance compared to the [18], because two paths are possible for transmitting the information and one path required two-hops and other required three-paths.

5 | CONCLUSION

Merging both wireless sensors networks and optical fiber in the Internet of Things (IoT) to form IoT-RoF is a promising technology. In this paper, new early fire-detection IoT-RoF is designed, the proposed design considered data journey from the sensors to the early alarm system. In addition, new protocol has been proposed, named as best remote antennas unit selection (BRAUS), the selection method based on the new proposed method as a function of number RAUs, fiber optic length, and distance. Two metrics have considered, outage probability and bandwidth efficiency, and both are formulated mathematically, driven and analyzed in terms of number of the RAUs and fiber optics length. The outage probability of proposed protocols reduced by 65% compared to recent works; in addition, the bandwidth efficiency of the proposed protocol is increased by 34% compared to recent works. As future suggestion, design multiple RAU selection instead of the signal RAU which can improve system performance in terms of the outage probability, bit error rate, and power consumption.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

All data are available within manuscript.

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