Received: 6 October 2023 | Revised: 3 January 2024 | Accepted: 30 January 2024

IET Networks

DOI: 10.1049/ntw2.12117

The Institution of Engineering and Technology WILEY

ORIGINAL RESEARCH

Investigating delay of the media access control protocols for IoT-RoF using quantum entanglement

Shakir Salman Ahmad | **Hamed Al-Raweshidy** | **Rajagopal Nilavalan**

Department of Electronic and Electrical Engineering, College of Engineering, Design and Physical Sciences, Brunel University London, Uxbridge, Middlesex, UK

Correspondence
Hamed Al-Raweshidy.
Email: hamed.al-Raweshidy@brunel.ac.uk

Funding information
Brunel University London

Abstract

One of the significant challenges of the Radio over fibre (RoF) Medium Access Control (MAC) protocol is the propagation delay. This delay can lead to serious issues, such as higher propagation delay resulting in collisions and unnecessary retransmissions. Quantum entanglement is an excellent candidate to overcome the propagation delay of the RoF MAC protocol. A new quantum MAC protocol is proposed, named the Quantum Entanglement-based MAC protocol (QE-MAC), in which Quantum Teleportation is utilised to address the propagation delay. Four entanglement states are employed to represent the control packets of the classical MAC protocol, and data is transmitted over the classical channel. Instead of using control packets such as acknowledgement, request to send, and Clear to send, state transitions are employed. This approach avoids the delay and collision issues associated with control packets, resulting in a significant improvement in network performance. The delay, duty cycle (DC), and power consumption of the proposed QE-MAC protocol are formulated and derived. The protocol is evaluated in terms of delay, DC, and power consumption, demonstrating superior performance compared to the classical RoF MAC protocol. In comparison to published works, our proposed approach has successfully reduced both delay and power consumption by 35%.

KEYWORDS
5G mobile communication, ad hoc networks

1 | INTRODUCTION

1.1 | Preliminaries and background

The 802.11 Radio over fibre (RoF) architecture's primary strength is that it brings together the capacity as well as transparency of optical fibre networks with the adaptability, simplicity, and portability of wireless networks. Furthermore, because RAUs may be located closer to mobile stations, coverage can be improved, air propagation can be constrained, and transmission power can be reduced [1, 2].

Next-generation applications, such as the tactile Internet, have stringent criteria that can only be met by RoF technology [3, 4], making it the ideal choice for centralised or cloud-based radio access networks. However, major challenges and limitations of existing medium access control (MAC) protocols issue arises when IEEE 802.11 is used over RoF. While the 802.11 MAC protocol is optimised for delays of less than 1 picosecond, the delay that is introduced into a RoF network is 5 picoseconds for every kilometre of fibre. The present IEEE 802.11 MAC protocol suffers from a decline in performance or even causes the network to fail owing to a rise in collisions and acknowledgement (ACK) timeouts. [5]. Thus, the existing protocol must be modified to account for the impacts that the additional propagation of fibre generates for the protocol to be effective and make full use of the aforementioned benefits of 802.11 RoF networks.

To address the challenge posed by RoF (Radio over Fibre), there are two potential solutions to consider. The first involves the design of an appropriate MAC protocol capable of accommodating the propagation delay associated with fiber optic transmission while carrying the signal to the central office [6, 7]. The second potential solution lies in the utilisation of quantum entanglement, which effectively eliminates the propagation delay of the control packets of the MAC protocols in RoF systems.

Sensors in Internet of Things technology play a pivotal role by acting as data collection points, capturing and transmitting real-time information from the physical world to the digital realm. These devices enable the monitoring and control of various parameters, fostering a connected environment where data-driven insights drive smarter decision-making and enhance overall efficiency in diverse applications, such as healthcare, smart cities, and industrial automation.

The data collected by the sensors must be efficiently transmitted to a central point for processing. Typically, sensors are connected to the central point through a wireless channel, which can be susceptible to numerous impairments, especially in forest and terrain areas. Therefore, transmitting collected data over fibre optics, known as RoF, proves to be a more suitable candidate in such challenging environments.

In this work, IoT-RoF Quantum Entanglement is proposed and designed to provide reliability and minimise the effect of the control packets which directly affect the problem of the RoF propagation delay. The proposed paradigms are depicted in Figure 1, where each of the five regions serves a distinct purpose within the larger IoT- RoF system. The following is a brief overview of the proposed paradigm in this work.

Sensors (which may be anything from webcams to smoke alarms to carbon monoxide detectors) are randomly or regularly dispersed in the first zone, which is called the "sensors region." After data has been gathered by sensors, it is transmitted to the master node using the protocol that will be detailed in the next section. In contrast to standard sensors, the master node was more capable, had a longer battery life, and was physically bigger. When the Master node receives sensor data, it passes it along to the Remote Antenna Unit (RAU). Part 2: The RAU This part of the network is responsible for receiving data and converting it from an electrical signal to an optical signal before sending it over an optical cable. Region 3, Quantum entanglement: in this region, received signal either represented by entangled state (only control packet) or transmitted directly over fibre optics (only information). Control packet will be represented by entangled state, each state will be exchanged over between RAU and base-station and it will not pass to the region 4. Data from the fibre optic is received at the base station, also known as the super master node, where the optical signal has been transformed to an electrical one. The primary responsibilities of the super master node are to (1) process the data and (2) transfer the processed data to region four (by selecting the appropriate department). Region 4 is where processed data arrives before being stored and examined by the relevant departments.

This paper introduces a novel concept wherein the control packets of the classical MAC protocol are substituted with quantum entanglement state transitions. It is important to note that data transmission remains conventional and follows classical methods. The rationale behind employing state transitions for control packets lies in harnessing the teleportation properties of quantum entanglement. Since the state is predefined between the receiver and transmitter, there is no need for delay or transition time to convey control packets. This ensures a smooth representation of control information without introducing additional latency.

Several studies have recently been interested in the phenomenon of quantum entanglement. However, no works have explored RoF with quantum communication using wireless sensing networks, and no works have analysed MAC protocols using quantum entanglement in IoT-RoF, Figure 2. Furthermore, no work has analysed the latency, duty cycle (DC), or power use of an IoT-RoF based on quantum entanglement analytically. This work's contribution may be summed up as follows:

1. For the first time, this paper proposes a new architecture of IoT-RoF based on quantum entanglement, in which sensors collect data from their surroundings and communicate that data to a decision-making section.
2. The proposed IoT-RoF quantum entanglement-based has two links, one classical link that is used to transmit the data,

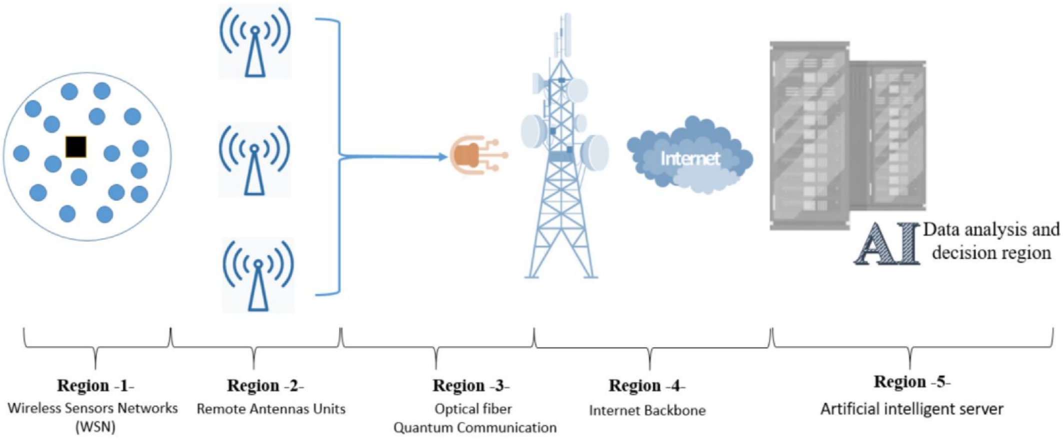

FIGURE 1 Envisioned communication scenario of the IoT-RoF Quantum Entanglement.

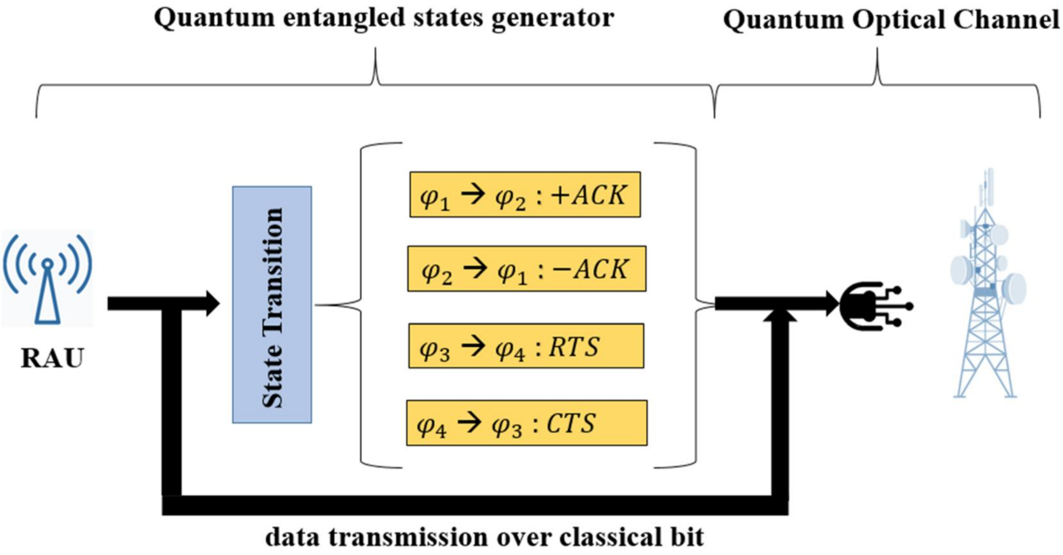

FIGURE 2 State transition of the proposed protocol.

and the other is quantum entanglement to transmit the control MAC protocol packets. Quantum Entanglement-based MAC protocol (QE-MAC), the proposed protocol, has had its latency mathematically modelled and drove down by 35% in comparison to prior studies.

3. Furthermore, QE-duty MAC's cycle and power consumption have been theoretically proposed and driven, resulting in a 35% reduction in both metrics compared to prior studies.

The rest of the paper is organised as follows. Related work details of quantum entanglement, are given in Section 2. MAC protocol over IoT-RoF is highlighted in Section 3, which include related work of the MAC protocol of the IoT-RoF and delay analysis of the MAC protocol over IoT-RoF. In Section 4, the proposed protocol, QE-MAC is discussed, then the delay is analysed and modelled. Section 5 focuses on the DC and energy use of the proposed QE-MAC protocol. Using the proposed works, Section 6 demonstrates that the proposed protocol is valid. Section 7 should include a summary and suggestions for moving forward.

1.2 | Related work: quantum entanglement

There is no work in the literature that is related to Quantum MAC protocol using entanglement; however, there are rich research studies of the entanglement in the communication and other applications, including quantum cryptography, distributed quantum computing, quantum sensing (e.g. multipartite entanglement for quantum metrology and spectroscopy; quantum machine learning), and it offers advantages to quantum [8].

The phenomenon of quantum entanglement, first seen in the 1930s, has the potential to continue surprising scientists for years to come. Today, it is evident that entanglement possesses many hitherto indescribable classical qualities and that it may be used to underpin a wide variety of novel ways to communication. Teleportation, quantum encryption, and other forms of high-tech quantum communication rely heavily on the properties of quantum entanglement. In addition to providing a solid basis for providing secure communication, the peculiar nature of quantum physics known as quantum entanglement is also an important factor. In cases when the two points are so intertwined that they cannot be separated. Both conventional bits (through the superdense coding protocol; and quantum bits (via the quantum teleportation protocol) may be sent using entanglement-based transmission [9].

Possible advantages of quantum communications include secure key creation, entanglement spread, and the efficient transport of quantum information [10]. With no bounds on local operations or two-way classical communication, we need to find the best point-to-point rates that may be achieved between two distant participants at the endpoints of a quantum channel in order to complete any of these activities. Without quantum repeaters, the maximum achievable rates are limited to the two-way aided capacities. This work establishes these skills for a wide variety of fundamental channels, such as bosonic lossy channels, quantum-limited amplifiers, dephasing, and erasing.

Channels in arbitrary dimension, by building an upper bound based on the relative entropy of entanglement and developing a dimension-independent technique that is called 'teleportation stretching'. We specifically pinpoint the precise rate-loss tradeoff that is inherent to every technique for distributing quantum keys. Our results establish the bounds of point to point (P2P) quantum communications and give comprehensive and exact standards for quantum repeaters. The protocol stability and performance are analysed through extensive simulations on a supercomputing cluster using a custom-built discrete-event simulator for quantum networks.

Through a thorough protocol implementation in our simulator, we are able to properly compare data from the network allocation vector hardware with the physical simulation model. First, we see that our protocol has little effect on system performance even in a regime with severe losses of conventional control signals. Next, we examine our protocols' throughput, latency, and other performance measures, as well as the tradeoffs between those metrics and entanglement quality, over 169 unique simulated situations. Finally, we launch an investigation into scheduling algorithms for quantum networks with the goal of improving protocol performance across a variety of scenarios [11].

Although entanglement's benefits to quantum information processing are enormous, its practical implementation is limited by issues such as loss and noise [12]. For decades, researchers have known that entanglement may greatly improve the classical transmission capacity of lossy and noisy bosonic channels. However, no efficient encoding or decoding algorithms have been developed to take use of this knowledge. Here, we detail entanglement-assisted communication scenarios and the structured encoding and decoding systems that might facilitate them. In particular, we demonstrate that the basic restriction on covert communication without the aid of entanglement may be circumvented by using phase encoding on an entangled two-mode squeezed vacuum state, which saturates the entanglement-assisted classical communication capacity of a highly noisy channel. We then develop receivers for the best possible procedures for testing hypotheses using discrete phase modulation and for estimating noisy phases using continuous phase modulation. Our findings open the door to entanglement-enhanced communication and sensing in the microwave and radio frequency spectrums.

Many useful technologies, such as remote quantum entanglement-enabled distributed quantum computing, encrypted communication, and precise sensing, are on the horizon [13]. We think about the possibility of distributing entanglement at a high rate across numerous pairs of users concurrently using a quantum network, which consists of nodes with limited quantum processing capabilities coupled through lossy optical connections. By taking use of the variety of numerous pathways in the network, the protocols we propose for such quantum "repeater" nodes allow a pair of users to achieve significant increases in entanglement rates over utilising a linear chain of quantum repeaters. We also design repeater methods that allow several user pairs to create entanglement concurrently at speeds that considerably beyond the time-sharing capabilities of individual entanglement flow assistance. Our findings imply that probabilistic Bell-state measurements and the use of short-coherence-time quantum memory may have a much greater effect on quantum networks than can be gleaned from an analysis of linear repeater chains. With this foundation, researchers may more easily bridge the gap between quantum memory physics, quantum information theory, quantum error correction, and computer network theory to provide a generic theory of quantum networks.

Large strides have been made in the last decade in experimentally realising the components of quantum repeaters [14]. There have been proposals for repeater architectures that use multiplexed quantum memory to speed up the pace at which entanglement is shared, but it remains a difficulty to keep entanglement consistent across long-distance connections. Here, we devise a quantum router architecture to facilitate entanglement fluxes over quantum networks; it consists of multiple quantum memories interconnected in a photonic switchboard. We use an event-based simulator to determine the rate and fidelity of entanglement distribution in this design and discover that the router enhances entanglement fidelity with increasing multiplexing depth while maintaining a constant rate. The router makes it possible to achieve the same level of fidelity that is possible via lossless lines, regardless of the amount of channel loss. Furthermore, without needing global network information, our technique automatically prioritises entanglement flows throughout the whole network. Since the suggested design makes use of existing photonic technology, it paves the way for the rapid deployment of multinode quantum networks in the not-too-distant future.

Separated observers may produce a limited number of entangled pairs of arbitrary high purity by performing local operations on a supply of not-too-impure entangled states (such as singlets exchanged across a noisy channel) (e.g. near-perfect singlets) [15]. These may then be used to reliably transfer quantum states between observers, allowing for the transmission of quantum information despite the channel's noise.

Secure communication [16], distributed quantum computing, enhanced sensing, and fundamental tests of quantum physics might all benefit greatly from the propagation of entanglement between nodes in a large-scale quantum network. For networks with more than two nodes, entanglement formation between them must outpace decoherence. Once this crucial point is crossed, probabilistic entangling techniques may be included into a robust building block that reliably establishes distant entangled linkages at scheduled intervals. Here, 2-m-long wires is used to put diamond spin qubit nodes closer together and overcome this barrier. Three orders of magnitude faster than the two-photon protocols demonstrated on this platform in the past, we develop a much appreciated single-photon entanglement technique with entangling speeds up to 39 Hz. The rate of de-coherence of distant entangled states is also reduced to 5 Hz by dynamical-decoupling, which we implement simultaneously. We employ these results in conjunction with efficient charge-state management as well as spectrum diffusion mitigation to successfully transmit a new remote state with an average entanglement fidelity of more than 0.5 on every clock cycle of 100 ms with no pre- or post-selection. These findings prove a fundamental component for long-range quantum networks and pave the way for entanglement propagation between dispersed nodes.

Quantum physics relies on entanglement as its fundamental mechanism [17]. Most notably, while observing measurements of two or more entangled particles, audiences will observe relationships that defy conventional statistical explanation. To fully realise its promise as a valuable resource, especially for scalable long-distance quantum communication, the generation of entanglement between geographically distant massive quantum systems is seen as a crucial first step. Here, we show how to create and analyse the much-touted entanglement between the spins of two rubidium-87 atoms held in magnetic traps 20 m apart. Our results prove the viability of a game-changing resource for fundamental experiments in quantum physics as well as quantum information science.

To the best of the author's knowledge, this work represents a novel approach that has not been explored previously. It involves the utilisation of entanglement phase change as an alternative to the conventional use of control packets in traditional MAC protocols. This innovative approach is expected to significantly enhance system performance while concurrently reducing power consumption and latency.

2 | MEDIUM ACCESS CONTROL PROTOCOL OF RADIO OVER FIBER

IEEE 802.11 wireless local area networks(WLANs) are among the most popular types of wireless networks due to their versatility and widespread use. Access networks that cover large regions at low cost can be made possible in rural areas, thanks to long-range WLANs employing high-gain antennas or RoF technology. Given that the access point (AP) in a high-gain antenna WLAN is physically separated from the stations (STAs), the AP utilises the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol to send and receive data with the traditional stations (STAs) [6, 7].

Remote communities can benefit greatly from wide-area, low-cost access networks made possible by long-range WLANs. Because it produces unanticipated frame collisions, the lengthy propagation delay between an AP and stations (STAs) in a WLAN greatly reduces the throughput and creates a throughput imbalance. This paper provides a concise overview of the difficulties brought on by extended propagation delays in the WLAN's MAC mechanism. To combat the loss in throughput caused by delays and the disparity in throughput between the uplink and the downlink in WLANs, a MAC protocol is proposed. To prevent frame conflicts caused by delays, the AP in the protocol increases the Network Allocation Vector time of a Clear to send (CTS) frame to shield an ACK frame before sending its own data frame. Based on the Bianchi model, the throughput estimate for the proposed technique [6, 7].

This research investigates the performance degradation that occurs when extending the reach of an IEEE 802.11 network with single-mode fibre. The study reveals that an increase in fibre length results in a decline in data throughput. Additionally, it is noted that the network experiences downtime due to MAC protocol timeout settings long before the physical layer's restrictions come into play. The analysis utilises the IEEE 802.11ac and ac-gnu versions of the distributed coordination function (DCF). To gather data and establish a baseline for comparison, an experiment is conducted. Subsequently, the OPNET simulation platform is employed to validate and refine the findings. Finally, the research provides an analytical approximation of these conclusions, enabling designers of Radio-over-fibre (RoF) systems to anticipate data throughput rapidly and reliably based on the exact specifications of their network. Notably, this study is the first of its kind to focus on a long-range fibre network [18].

As the name implies, Radio over Fibre (RoF) systems transparently distribute radio signals from an AP to distributed far antennas over an optical network, bringing together the mobility and flexibility of wireless networks with the capacity and openness of fibre-fed networks. New techniques at the physical and MAC levels are included in the recently published IEEE 802.11n standard, allowing for increased throughput. It is demonstrated, the additional propagation delay generated by optical fibres in RoF systems is mitigated by the aggregation method given by IEEE 802.11n. Furthermore, it revealed that the IEEE 802.11n frame aggregation process in RoF networks requires the slot time parameter value to be adapted to maintain efficiency [19].

In this research, we look at how well the IEEE 802.11 MAC performs in terms of throughput when the physical layer is implemented in the cloud. In order to evaluate throughput, a suggested analytical model takes into account the possibility of a late ACK arriving at a time other than zero. The suggested model is used to analyse both traditional DCF and the Block ACK improvement included in the most recent IEEE 802.11 specifications. Data demonstrates that activating Block ACK considerably mitigates the performance reduction brought on by network delay variation in standard DCF [20].

In this study, a MAC protocol for a RoF-based WLAN to operate alongside conventional CSMA/CA-based WLANs is proposed. Long delays in communication occur between APs and stations in RoF-based WLANs (STAs). It is unreasonable for a RoF-based WLAN to coexist with older WLANs using the traditional CSMA/CA protocol, since the propagation delay generates unexpected frame collisions. The proposed system's RoF AP continuously delivers frames during transmission and reception in the traditional WLAN to prevent frame conflicts. This guarantees that the AP's sent frame will reach its intended STA one short inter-frame inter space (SIFS) period after the channel went silent. Since frame conflicts are less likely to occur thanks to the suggested strategy, the RoF-based WLAN's throughput is improved. The suggested technology also allows for adaptive modification of the transmission probability, which facilitates equitable wireless channel sharing between the RoF-based WLAN and the older WLANs. For IEEE 802.11a/b/g WLANs [21].

Channel access performance in wireless networks, such as IEEE 802.15.4-based wireless LANs, may be improved by combining the advantages of carrier-sense multiple access with collision avoidance (CSMA/CA) with time-division multiple access. In example, a hybrid CSMA/CA-TDMA method may improve the performance of a classic CSMA/CA-based MAC system in crowded networks without sacrificing scalability. In this research, we provide models for both decentralised and centralised channel access that use Markov decision process (MDP)-based transmission techniques to make optimal use of the available contention-free and contention-prone times. If the amount of traffic given is less than the maximum capacity of the channel, the models use the buffer state as an indicator of congestion. We generalise the models to account for the signal attenuation experienced by hidden nodes as a result of channel fading. Results from simulations indicate that the MDP-based distributed channel access technique works better than the conventional slotted CSMA/CA approach. The centralised approach is superior to the scattered one but needs access to the network's overall data [22].

2.1 | Delay analysis of conventional distributed coordination function in Radio over fibre

The primary goals of the IEEE 802.11 MAC sublayer are to 1) guarantee the safe arrival of user data despite the unpredictability of the wireless channel, 2) guarantee equitable access to the wireless channel, and 3) guarantee data confidentiality and integrity. The IEEE 802.11 MAC uses two mechanisms—the mandatory two-way handshaking method and the discretionary four-way handshaking approach—to guarantee the secure transmission of user data across the wireless channel.

Delay of conventional DCF with/without request to send (RTS)/CTS packet: Delay of conventional DCF without RTS/CTS packet. Two-Way hand shaking mechanism without RTS/CTS packets as follows can be summarised:

1. A node which wishes to transmit a packet, first it must sense the medium for a period of distributed inter-frame space (DIFS) plus a back off duration. The back off duration is a pseudorandom time interval which is applied to avoid collisions between nodes wishing to access the medium.
2. If the medium is idle for the mentioned period, the node can access the medium and initiate a transmission.
3. Receivers wait a SIFS duration before transmission an ACK packet.
4. Then, new contention starts, and other stations (including the transmitter) start their distributed inter-frame space and Backoff timer.

The mathematical representation of the average slot duration of the Two-Way hand shaking mechanism without RTS/CTS packets can be expressed as follows:

$$E[slot] = Pidle\ Ts + Psuc\ T + (1 - Psuc - Pidle)\ Tc + Psuc\ 2\alpha + (1 - Psuc - Pidle)\ 2\alpha \tag{1}$$

In which

$Pidle$: the probability that no sensor accesses a given slot.

Ts: denotes the CSMA slot length.

$Psuc$: Probability that just one sensor accesses a slot.

T: defined as the total time to transmit a packet.

T_c: the average time the channel is sensed busy during a collision.

α: Propagation delay time.

The mathematical expression of the P_{idle} for the N sensors, where N sensors are randomly and independently accesses a slot time with probability τ is given as, $Pidle = (1 - \tau)^N$, then mathematical expression of the $Psuc$ is expressed as follows:

$$Psuc = N\,\tau(1 - \tau)^{N-1} \tag{2}$$

The mathematical expression of the $T = T_c$ which include DIFS time, SIFS time, DATA time, Backoff time, and ACK packet time, it is given as follows:

$$T = T_{DIFS} + T_{SIFS} + TDATA + T_{BC} + TACK \tag{3}$$

In which, T_DATA is the data packet consists of a preamble (T_P), physical header (T_{PHY}), MAC header (T_{MAC}), MAC frame body (T_{BODY}), and frame check sequence (T_{FCS}), the time to transmit a data packet is given by the following,

$$TDATA = T_P + T_{PHY} + T_{MAC} + T_{BODY} + T_{FC} \tag{4}$$

where T_{BC} is given as follows:

$$T_{BC} = \frac{CW_{min}\ T_s}{2}$$

Where slot (0, CW) is a pseudorandom integer from a uniform distribution in the interval [0, CW], CW is the contention window size, and slot time is a fixed time value defined by protocol When the destination node receives the packet, The CW size is limited in the interval is $CWmin \le CW \le CWmax$, where CWmin is the minimum and CWmax is the maximum CW size. After a successful transmission, CW is set to CWmin, whereas after a retransmission, it is doubled, $CWi = CWi{-}1 \cdot 2$.

Delay of conventional DCF with RTS/CTS packet: On the other hand, we can summarise the four-Way hand shaking mechanism with RTS/CTS packets as follows:

Delay of conventional DCF with/without RTS/CTS packet of RoF: The main advantage of the 802.11 RoF architecture is the combination of flexibility, low complexity, and mobility offered by wireless networks with the capacity and transparency of optical fibre networks. Other advantages are the concentration of complexity in CS, allowing the use of simpler RAUs, enhanced coverage, and limitation of air propagation and transmission power, since the RAUs can be placed closer to mobile stations. Furthermore, RoF technology is described as the ideal solution for centralised or cloud-based radio access networks, capable of serving the stringent demands of future applications, like tactile Internet, in terms of reliability, data rate and latency [6, 7].

However, a significant problem arises when using IEEE 802.11 over RoF. The 802.11 MAC protocol is designed for

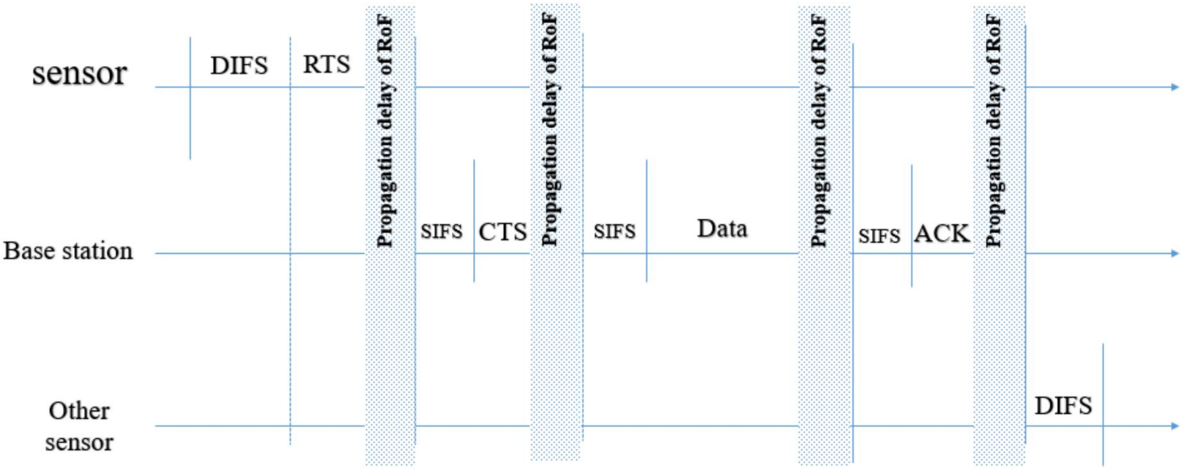

FIGURE 3 IEEE 802.11 Medium Access Control (MAC) of the Radio over fibre (RoF) with consideration of RTS/Clear to send (CTS) control packet.

propagation delay less than 1 microsecond, whereas the injected delay to RoF network is 5 microsecond per kilometre of fibre. This fact degrades or even causes the overall performance of such a network to collapse completely due to increased number of collisions or acknowledgement (ACK) timeouts, when the existing IEEE 802.11 MAC protocol is used [6, 7].

In a conventional DCF procedure, the ACK frames never collide with other frames except when hidden terminals exist because ACK frames are highly prioritised, that is, they are transmitted using the SIFS period. However, in long-distance WLANs, the ACK could collide with other frames transmitted by the other STAs. Delay of conventional DCF without RTS/CTS packet of RoF: In this paper, collision due to late ACK packet. In a conventional DCF procedure, the ACK packet never collides with other data packet or data frame except when hidden terminals exist because ACK packet is highly prioritised, that is, they are transmitted using the SIFS period. However, in Rof system, the ACK could collide with other packets transmitted by the other sensors (stations, STA). Figure 3 shows an ACK collision. When an STA completes the transmission of a data frame to an AP, the AP and transmitter STA should wait $T_{ackarrival} = SIFS$, time required to receive the ACK packet, however, and due to delay of fibre optic, the ACK packet will be received at time greater than $T_{ackarrival}$, which is defined as $T^{RoF}_{ack\ arrival} = SIFS + T_{ACK} + DIFS$, that will cause collision with other data frame transmitted from other STA.

Algorithm 1 Channel access method of the RoF

Require: CW_{min} and CW_{min}
Begin

```
1. Sensor collect data from environment.
2. Sensor waits for DIFS and random Backoff time.
3. If the channel is free,
4. Sensor transmits their data over free channel.
5. If data received correctly by the receiver,
6. Receiver and sender wait SIFS time.
7. Then, receiver send + ACK to sender.
8. Else if, data not received correctly by the receiver,
9. Receiver and sender wait SIFS time.
10. Then, receiver send - ACK to sender.
11. End
12. End
13. Else if the channel not free,
14. Sensor waits for second round of competition
15. End
```

In what follows, the mathematical representation of the average slot duration of the Two-Way hand shaking mechanism without RTS/CTS packets of the RoFcan be expressed as follows:

$$E[slot]_{RoF} = Pidle\ Ts + Psuc\ T + (1 - Psuc - Pidle)\ Tc + Psuc\ 2\alpha + (1 - Psuc - Pidle)\ 2\alpha + \underbrace{2\alpha + T^{ACK}c}_{delay\ due\ to\ collision\ and\ propagation\ of\ Rof} \tag{6}$$

The additive time due to using RoF system is expressed as follows:

$$T^{RoF}_{delay} = 2\alpha + T^{ACK}c$$

Delay of conventional DCF with RTS/CTS packet of RoF: When the conventional DCF with RTS/CTS packet of RoF is used, the collision will occur again from ACK, in addition, delay will be more due to RTS/CTS packet with travel over long distance which fibre optics. In this scenario, the mathematical representation of the average slot duration of the Two-Way hand shaking mechanism with RTS/CTS packets of the RoF can be expressed as follows:

$$\begin{aligned} E[slot] = {} & Pidle\ Ts + Psuc\ \left(T + T_{RTS+CTS} + T_{RTS+CTS}^{delay,RoF}\right) \\ & + (1 - Psuc - Pidle)\left(T_{RTS+CTS}^{delay,RoF} + T_{RTS+CTS} + Tc\right) \\ & + \underbrace{Psuc\ 2\alpha + (1 - Psuc - Pidle)\ 2\alpha}_{\overline{\alpha}} \\ & + \underbrace{2\alpha + T^{ACK}c}_{delay\ due\ to\ collision\ and\ propagation\ of\ Rof} \\ E[slot] = {} & Pidle\ Ts + Psuc\ F_T\left(T_{RTS+CTS}^{delay,RoF}\right) \\ & + Pro.\ F_{Tc}\left(T_{RTS+CTS}^{delay,RoF}\right) + \overline{\alpha} + F\left(\overline{\alpha}\right) + F\left(\alpha\right) \end{aligned} \tag{7}$$

Algorithm 2 Channel access method of the RoF with RTS/CTS

```
Require: $CW_{min}$ and $CW_{min}$
Begin
  1. Sensor collect data from environment.
  2. Sensor waits for $DIFS$ and random $Backoff$ time.
  3. If the channel is free,
  4. Sensor transmits $RTS$ packet to the receiver.
  5. Both receiver and transmitter wait $SIFS$ time
  6. Receivers send $CTS$ packet back to sender.
  7. Transmitter wait $SIF$ S and then send data to the receiver.
  8. If data received correctly by the receiver,
  9. Receiver and sender wait $SIFS$ time.
  10. Then, receiver send $+$ $ACK$ to sender.
  11. Else if, data not received correctly by the receiver,
  12. Receiver and sender wait $SIFS$ time.
  13. Then, receiver send $-$ $ACK$ to sender.
  14. End
  15. End
  16. Else if the channel not free,
  17. Sensor wait for second round of competition
  18. End
```

3 | DELAY OF PROPOSED QUANTUM ENTANGLEMENT-BASED MAC PROTOCOL

3.1 | Delay of quantum entanglement-based without RTS/Clear to send packet

Based on the photon state transition, both Algorithms 1 and 2 are modified. The quantum procedures will replace the signalling packets which are + ACK and − ACK into state transition, where each transition will represent one of the controls (signalling) packets. The required time to change the polarisation between two ends is zero, for this reason, the time (propagation delay) due to long distance or fibre optic will be zero in this case and disadvantage can be totally avoided in the RoF system. When the quantum is utilised, the delay due to laser source, T_{laser}, and detector, $T_{detector}$, are included in the total delay of the QE-MAC [22, 23], therefore, the delay is expressed as follows:

$$\begin{aligned} E[slot] = {} & Pidle\ Ts + Psuc\ \left(T + T_{laser} + T_{detector}\right) \\ & + (1 - Psuc - Pidle)\left(T_{laser} + T_{detector} + Tc\right) \\ & + Psuc\ 2\alpha + (1 - Psuc - Pidle)\ 2\alpha \end{aligned}$$

$$\begin{aligned} E[slot] = {} & Pidle\ Ts + Psuc\ F\left(T_Q\right) \\ & + (1 - Psuc - Pidle)\ F\left(T_{\overline{Q}}\right) + F\left(\overline{\alpha}\right) \end{aligned} \tag{8}$$

For two packets, it should have four states, φ_1 and φ_2. The entangled QE-MAC without RTS/CTS packet of RoF algorithm is given below: Algorithms 3 and 4

Algorithm 3 Entangled DCF without RTS/CTS packet of RoF

```
Require: $CW_{min}$ and $CW_{min}$
State transition $\varphi_1 \rightarrow \varphi_2$ is represent $+$ $ACK$
State transition $\varphi_2 \rightarrow \varphi_1$ is represent $-$ $ACK$
Begin
  1. Sensor collect data from environment.
  2. Sensor waits for $DIFS$ and random $Backoff$ time
  3. If the channel is free,
  4. Sensor transmits their data over free channel
  5. If data received correctly by the receiver,
  6. Receiver and sender wait SIFS time.
  7. Then, State transition $\varphi_1 \rightarrow \varphi_2$ (+ ACK)
  8. Else if, data not received correctly by the receiver,
  9. Receiver and sender wait SIFS time.
  10. Then, State transition $\varphi_2 \rightarrow \varphi_1$ (− ACK)
  11. End
```

```
    End
Else if the channel not free,
    Sensor waits for second round of competition
End
```

3.2 | Delay of quantum entanglement-based without RTS/Clear to send packet

Based on the photon state transition, both Algorithms 1 and 2 are modified. The quantum procedures will replace the signalling packets which are + ACK, − ACK, RTS and CTS into state transition, where each transition will represent one of the control (signalling) packets. The required to Change the polarisation between two ends is zero, for this reason, the time (propagation delay) due to long distance or fibre optic will be zero in this case and disadvantage can be totally avoided in the RoF system. When the quantum is utilised, the delay due to laser source, T_{laser}, and detector,$T_{detector}$, are included in the total delay of the QE-MAC and, therefore, delay is expressed as follows:

$$\begin{aligned} E[slot] &= Pidle\ Ts + Psuc\ \ (T + T_{RTS+CTS}\ + T_{laser} + T_{detector}) \\ &\quad + (1\ -\ Psuc\ -\ Pidle)\ (T_{laser} + T_{detector} + T_{RTS+CTS} + Tc) \\ &\quad + Psuc\ 2\alpha + (1\ -\ Psuc\ -\ Pidle)\ 2\alpha \\ E[slot] &= Pidle\ Ts + Psuc\ \ F\left(\overline{T_Q}\right) \\ &\quad + (1\ -\ Psuc\ -\ Pidle)\ F\left(\overline{T_Q}\right) + F\ (\overline{\alpha}) \end{aligned} \tag{9}$$

For three packets, we should have four states, φ_1, φ_2, φ_3 and φ_4. The entangled DCF without RTS/CTS packet of RoF algorithm is given below:

Algorithm 4 Entangled DCF with RTS/CTS packet of RoF

```
Require: $CW_{min}$ and $CW_{min}$
State transition $\varphi_1 \rightarrow \varphi_2$ is represent $+ ACK$
State transition $\varphi_2 \rightarrow \varphi_1$ is represent $- ACK$
State transition $\varphi_3 \rightarrow \varphi_4$ is represent $RTS$
State transition $\varphi_4 \rightarrow \varphi_3$ is represent $CTS$
Begin
Sensor collect data from particular environment.
Sensor waits for DIFS and random Backoff time.
If the channel is free,
    State transition $\varphi_3 \rightarrow \varphi_4$ (S packet transmitted)
    Both receiver and transmitter wait SIFS time
    State transition $\varphi_4 \rightarrow \varphi_3$ (CTS packet transmitted)
    Transmitter wait SIF S and then send data to the receiver.
    If data received correctly by the receiver,
        Receiver and sender wait SIFS time.
        Then, State transition $\varphi_1 \rightarrow \varphi_2$ (+ ACK)
    Else if, data not received correctly by the receiver,
        Receiver and sender wait SIFS time.
        Then, State transition $\varphi_2 \rightarrow \varphi_1$ ( − ACK)
    End
End
Else if the channel not free,
    Sensor waits for second round of competition.
End
```

4 | POWER CONSUMPTION AND DUTY CYCLE OF PROPOSED QUANTUM ENTANGLEMENT-BASED MAC PROTOCOL

In this subsection, we address the DC and power for the classical communication of CSMA/CA based on IEEE 802.11 of the RoF, then, DC and power of the Proposed QE-MAC is derived. Duty cycle is calculated as the fraction of time that a system is in an "active" state [24–26]. For the sensor transceiver, this is the time the transceiver is ON (RF activity time), regardless of if it is transmitting data, receiving data, or idly listening to a clear channel. The DC is computed as follows [24]:

$$Duty = \frac{T_{act}}{T_{sleep}}\ (1 + PER) \tag{10}$$

In which, T_{act} is the RF activity time, In this work, $T_{act} = E[slot]$, T_{sleep} is the time of sensor sleeping to maintain network lifetime. Where, PER is packet error rate and it is assumed very small, therefore, $1 + \text{PER} = 1$. The energy consumption is a function of the DC of RF activity and the average current during the activity period. Since the current consumption during data reception is always the same, energy consumption can be improved by lowering the transmission power and the overall transmission time. The complete average communication power P_{av} is computed as follows:

$$P_{av}\ = (Duty)\ V_{dd}\ I_{active} \tag{11}$$

where duty is the DC, V_{dd} is the RF module supply voltage, and I_{active} is the average RF active average current in one timeframe. Accordingly, the DC of the proposed Quantum Entanglement-based without RTS/CTS packet:

$$Duty_{Q} = \frac{Pidle\ Ts + Psuc\ \ F\left(T_{Q}\right) + (1\ -\ Psuc\ -\ Pidle)\ F\left(T_{\overline{Q}}\right) + F\ (\overline{\alpha})}{T_{sleep}} \tag{12}$$

$$P_{av}\ = \left(\frac{Pidle\ Ts + Psuc\ \ F\left(T_{Q}\right) + (1\ -\ Psuc\ -\ Pidle)\ F\left(T_{\overline{Q}}\right) + F\ (\overline{\alpha})}{T_{sleep}}\right) V_{dd}\ I_{active} \tag{13}$$

In what follows, the average power consumption Quantum Entanglement-based without RTS/CTS packet:

$$Duty_{\overline{Q}} = \frac{Pidle\ Ts + Psuc\ \ F\left(\overline{T_{Q}}\right) + (1\ -\ Psuc\ -\ Pidle)\ F\left(\overline{T_{\overline{Q}}}\right) + F\ (\overline{\alpha})}{T_{sleep}} \tag{14}$$

The DC of the proposed Quantum Entanglement-based with RTS/CTS packet:

$$P_{av}\ = \left(\frac{Pidle\ Ts + Psuc\ \ F\left(\overline{T_{Q}}\right) + (1\ -\ Psuc\ -\ Pidle)\ F\left(\overline{T_{\overline{Q}}}\right) + F\ (\overline{\alpha})}{T_{sleep}}\right) V_{dd}\ I_{active} \tag{15}$$

In what follows, the average power consumption Quantum Entanglement-based with RTS/CTS packet:

5 | RESULTS AND DISCUSSION

In this section, we assess the performance of the proposed IoT-RoF Quantum Entanglement through computer simulations. The simulations involve a randomly generated topology of sensors and master nodes situated within an area of 4 km × 4 km. Multiple RAU are distributed within the same area, with each RAU connected to a central office or base station via fibre optic, with a maximum length of 25 km. For the quantum channel, four photons are utilised. The proposed system employs two communication scenarios: one is classical for data transmission, and the second is quantum for sharing control packets in the state format. Complete parameters are detailed in Table 1.

Figure 4 shows the comparison of the Classic MAC protocol versus Quantum MAC protocol of the IoT-RoF with respect to the CWmin. According to the results shown in the Figure 5, we can summarise the results as follows:

1. Classic MAC protocol has less delay compared to the classic MAC protocol with RTS/CTS because control packets that increase the delay, however, the proposed Quantum MAC protocol has better performance compared to both MAC protocol and classic MAC protocol with RTS/CTS because all the control packets are voided, therefore, propagation delay also avoided.

TABLE 1 Simulation parameters.

Symbol	Definition	Value
CB	Channel bandwidth	20 MHz
R	Data rate	54Mbps
R_l	Retry limit	7
CW_{max}	Contention window max	15
CW_{min}	Contention window min	7
$SIFS$	Short interframe space	16 µs
T_s	Slot time	9 µs
α_w	Propagation delay—Wireless link	1 µs
α_{Fib}	Propagation delay—Fibre link	5 µs
TDATA	Time required for data	216 µs
TRT S; CT S; ACK	Time delay: RTS, CTS and ACK packets	24 µs
T_{laser}	Delay for laser propagation	1 µs
$T_{detector}$	Delay for detecting of laser	1 ns
N_{pho}	Number of photons	4
V_{dd}	RF module supply voltage	1.8 V
I_{active}	RF active average current	6.1 µA

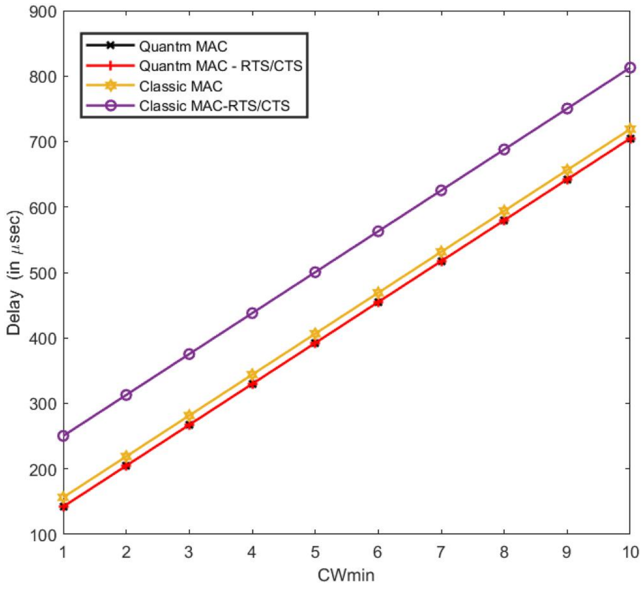

FIGURE 4 Classic Medium Access Control (MAC) protocol versus Quantum MAC protocol of the IoT-RoF.

2. In this result, beautiful observation is obtained, that both Quantum MAC protocol and Quantum MAC protocol with RTS/CTS have the same time delay, which means it is possible.
3. Moreover, the delay grows as CWmin increases. This is because a higher CWmin results in longer waiting times for each sensor before it can access the channel again.
4. The results indicate a notable matching between Quantum MAC with RTS/CTS and Quantum MAC. This matching arises because the delays associated with negotiation through RTS/CTS are effectively addressed through the utilisation of quantum entanglement.

Figure 6 illustrates a comparative analysis between the DC of classical communication and the DC of Quantum Entanglement in the context of IoT-RoF concerning CWmin. The results can be summarised as follows:

1. The observation emphasises that the DC of classical communication, particularly with RTS/CTS packets, is higher compared to the DC without the inclusion of RTS/CTS packets. This is because the Quantum Entanglement MAC protocol avoids the use of RTS/CTS and replaces it with a state transition.
2. Furthermore, it has been observed that the DC of Quantum Entanglement is less than both classical communication scenarios, with and without RTS/CTS packets. This reduction in DC can be attributed to the utilisation of a teleportation protocol in Quantum Entanglement, enabling the exchange of photon states without the need for any additional control packets.
3. Quantum Entanglement DC and DC of the classical communication increased with CWmin increases because it is increased the backoff time.

Figure 7 provides a detailed comparison of the power consumption between IoT-RoF utilising Quantum Entanglement and classical IoT-RoF, considering the variation in CWmin. The results indicate that Quantum Entanglement outperforms classical communication in terms of power consumption. This advantage is attributed to the use of the teleportation protocol in Quantum Entanglement, eliminating the need to transmit the photon state over the physical link and resulting in a significant reduction in power consumption.

6 | CONCLUSION

In this article, our focus is on introducing a comprehensive understanding of the delay, DC, and power consumption associated with the QE-MAC, which leverages the principles of Quantum teleportation. The aim is to shed light on the performance characteristics of this innovative protocol. Our results underscore the notable advantages of the proposed QE-MAC. Specifically, when compared to conventional MAC protocols, QE-MAC demonstrates superior performance in terms of delay, DC, and power consumption. These metrics are critical in evaluating the efficiency and effectiveness of a communication protocol within a network. One key observation is that, when QE-MAC is employed, the performance of the QE-MAC RTS/CTS packets closely aligns with that of QE-MAC without RTS/CTS packets. This finding holds

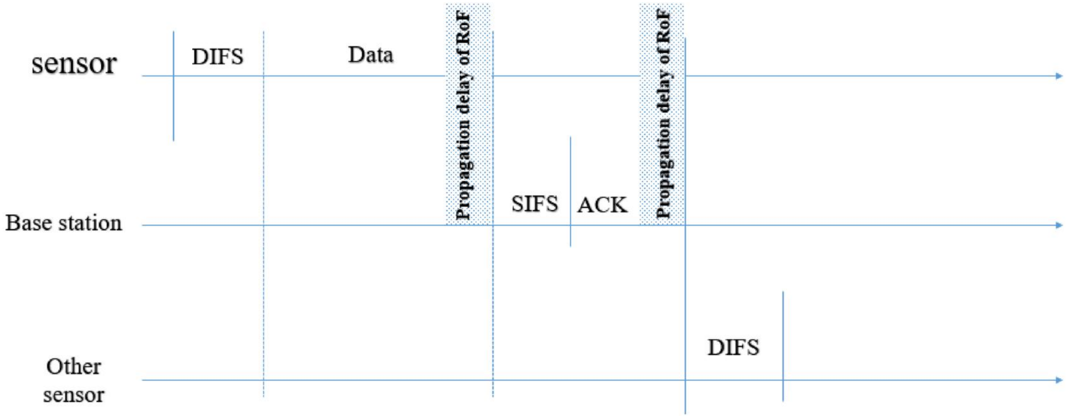

FIGURE 5 IEEE 802.11 Medium Access Control (MAC) of the Radio over fibre (RoF) with consideration of the propagation delay.

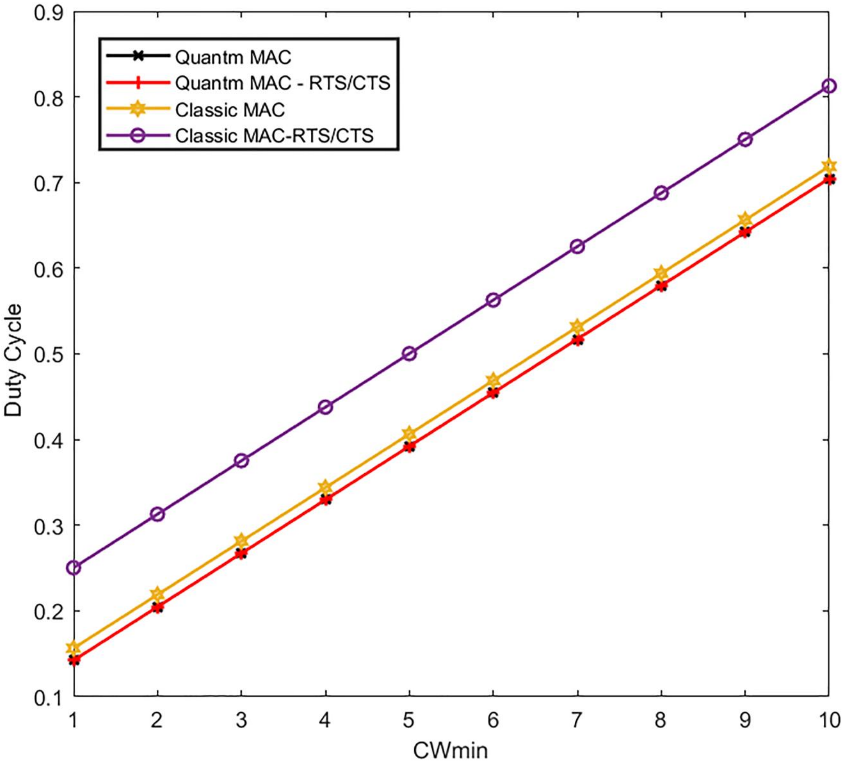

FIGURE 6 Duty cycle (DC) of the IoT-RoF Quantum Entanglement versus classical IoT-RoF.

significant implications for collision avoidance and data preservation, two fundamental aspects of network communication reliability. The ability of QE-MAC to maintain comparable performance with or without RTS/CTS packets underscores its robustness and adaptability in different scenarios. Moving forward, our results open avenues for future research. There is an opportunity to delve deeper into formulating throughput metrics in the presence of collisions, addressing a critical aspect of network performance. Additionally, exploring optimal power allocation strategies for both master and sensor nodes could further enhance the overall efficiency of the proposed QE-MAC. Future work could focus on formulating throughput in the presence of collisions and determining optimal power allocation for both master and sensor nodes. In comparison to published works, our proposed approach achieves a 35% reduction in both delay and power consumption. Future work could focus on formulating throughput in the presence of collisions and determining optimal power allocation for both master and sensor nodes.

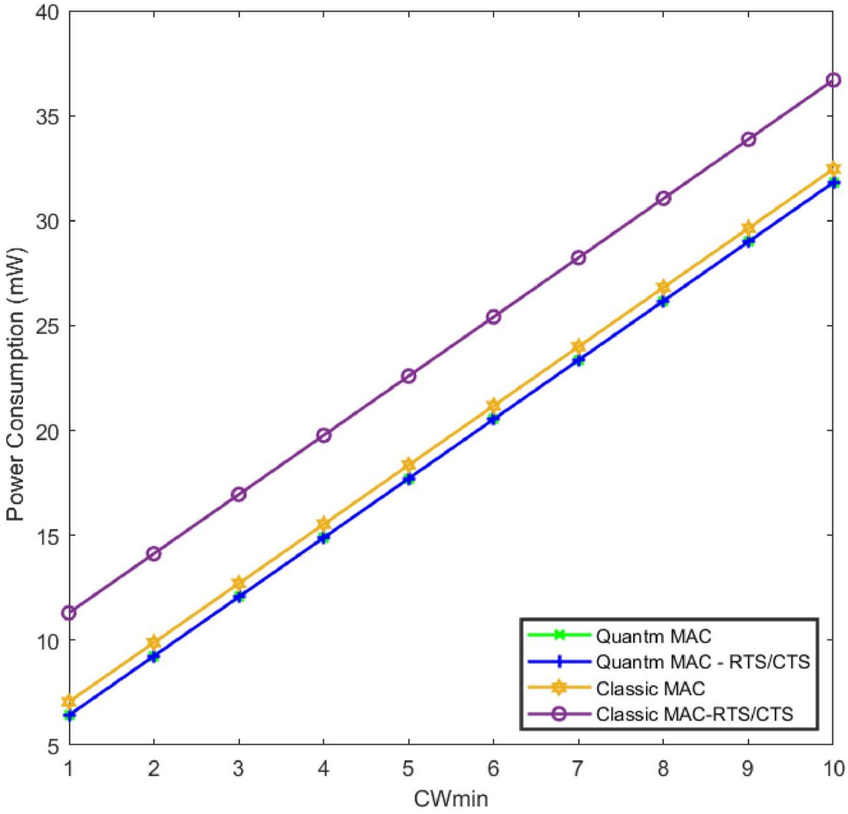

FIGURE 7 Power consumption of the IoT-RoF Quantum Entanglement versus classical IoT-RoF.

AUTHOR CONTRIBUTIONS

Shakir Salman Ahmad: Investigation; Methodology; Resources; Writing – original draft. **Hamed Al-Raweshidy**: Supervision; Writing – review & editing. **Rajagopal Nilavalan**: Supervision; Validation; Writing – review & editing.

ACKNOWLEDGEMENT

Brunel University London, Grant/Award Number:J066.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

All data necessary for verification and replication are provided within the manuscript.

ORCID

Shakir Salman Ahmad https://orcid.org/0000-0001-5244-8307

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How to cite this article: Ahmad, S.S., Al-Raweshidy, H., Nilavalan, R.: Investigating delay of the media access control protocols for IoT-RoF using quantum entanglement. IET Netw. 13(4), 324–337 (2024). https://doi.org/10.1049/ntw2.12117