Digital Object Identifier

Quality of Service of Quantum entanglement in Mobile Networks

YASSIR AL-KARAWI[1], RAAD S. ALHUMAIMA [2], HAMED AL-RAWESHIDY[3],
[1]Department of Electronic and Electrical Engineering,Brunel University London,UK (e-mail: 2002370@brunel.ac.uk)
[2]Department of Communications, University of Diyala, Diyala, Iraq (e-mail: 1234914@alumni.brunel.ac.uk)
[3]Department of Electronic and Electrical Engineering,Brunel University London,UK (e-mail: Hamed.Al-Raweshidy@brunel.ac.uk)

Corresponding author: Yassir Al-Karawi (e-mail: 2002370@brunel.ac.uk).

ABSTRACT There are many problems in cellular communications cannot be resolved traditionally. The quantum communications can add new dimensions, safety, encryption and solution to the traditional networks because of its robust physical strength. However, it is not entirely realised how to adapt the quantum into the traditional communications because it is not entirely utilised. This paper addresses the necessary guidelines and assessments for future quantum solutions to the standard mobile cloud networks. In particular, using entanglement phenomenon to increase the performance of the X2 application (X2-AP) protocol by minimising the overhead signalling, represented by the time and energy consumption the conventional cloud encounters. We intended to offer a delay reduction while adapting the quantum technique into the cloud by modelling the latency of both paradigms. Finally, increasing the number of photons has decreased the delay to about 40% compared to the traditional network. In addition, the energy efficiency in the quantum case has been increased while decreasing the power consumption by about 10%.

INDEX TERMS energy efficiency, handover, mobile networks, quantum teleportation.

I. INTRODUCTION

THE growing number of network's users (UEs) demanding higher bandwidth, low latency, low power utilization, and effective energy distribution [1], [2]. Concerning traditional communications, the improvement of next generation, especially 6G metrics is conclusive, a decrease in the transistor's size would not be feasible in the future because of production constraints [3], [4]. Likewise, a circuit should have twice every two years the number of industrial transistors; this rule also has a limit. Similarly, electrical systems are constrained in power consumption and processing delay [5]. Hopefully, the servers demand is minimized by offering cloud radio connectivity networks in conventional mobile networks to reduce the power consumption. In addition, by virtualizing the cloud core baseband (BBU) units in the cloud platform, the energy consumption is further reduced [6]. Additional solutions are suggested, like a software-defined network that improves the scalability and maintenance challenges while unifying the control level of possible networks [7]. Moreover, self-organising the configuration of networks shall predict the possible future events, which optimises their operations. Besides, some work has been done to maximise the usable bandwidth resources blocks. However, occupying the stingy amount of resource blocks shall come to an end due to the inherent low available bandwidth, and maximising these will no longer increase the spectral performance [8]. Therefore, the struggles continues in the classical communication even when the most effective technologies are used [9]. Not to mention the inherently unsolvable delay problem that is physically related to the distance of the channels, and processing delay. This causes the communication calls to be blocked and UEs outage [10]. Hence, the quantum domain may offer the required solution [11]. Generally, applying quantum methods to mobile communications is unusual. The truth is that quantum computation is incomplete itself [12]. Moreover, classical behaviors and quantum behavior vary tremendously [13]. Optical communications technologies have several quantum features represented by optical fibers, laser sources for photons to be produced, and the light on the receiver side to be sensed [14]. However, only one wave property is utilised and seen in the classical sense out of the two photon's characteristics. The photon operates based on how a photon is measured and modified in both wave and particle properties [15]. Recently, quantum computing applications and advances have been spreading, such as quantum entanglement, quantum routing, quantum repeating, quantum relay and encoder/decoder, quantum synchronization, quantum memory and quantum cryptography [16].

In the literature, the upcoming cloud networks has been a candidate for next generation, especially 6G, to reduce the power consumption of the traditional networks. By combining the base band units (BBUs) of the legacy sites in one place, leaving the cell site as simple as it contains the antenna, amplifier and radio frequency unit, called remote radio head (RRH). Less cooling, less total power consumption, less renting cost, more cooperative and collaborative procedure will be gained. However, some disadvantages have been assured such as the need to more complicated algorithm to run the network. In addition, more channel delay that is originated due to shifting the data plane processing to far-away data center. Furthermore, more significant number of signalling control planes contributes to higher power consumption, complexity, latency and increases the rate the blocking calls [17]. In contrast, the ideal handover must overcome the traditional procedure and offers less power consumption and less delay. In this work, we proposed a power and time delay saver approach that uses quantum entanglement to reduce the inherent signalling delay of the X2-AP protocol, classically used for the handover process. For that purpose, we have proposed a time delay model to measure the classical and quantum delays. The latter have caused some power consumption and energy efficiency trade offs within the quantum method compared to the traditional network. Nevertheless, a simplified power model have been proposed to calculate both classical and quantum network consumption. We may summarise the contributions of the proposed work as follow:

1) The already used X2-AP handover protocol causes large amount of signalling represented by the time and power consumption. Subsequently, quantum entanglement phenomena has been used as a handover process instead of the traditional method. The former can utilise a hidden channel amongst the generated photons to transfer the information amongst the mobile radio heads with zero delay.
2) The proposed method have replaced the successive classical signalling, each with corresponding entangled photon. Classically, when the remote heads tries to communicate with the each others asking for handover, the destination and source remote head uses classical signals with time and energy perspectives. The quantum method has replaced such communication by changing the behaviour of one of the entangled photons (suppose in the source remote head) to pass the information without a delay to the other photon (supposed in the destination remote head) to reduce the overall latency of the network.
3) Passing an information without delay means the power consumption can also be reduced. Classically such power consumption is originated from generating the classical signalling and transmit to the other network parties. In the quantum method, the consumption of generating the signals has been ignored. Rather, it was replaced by a consumption that is originated from generating the entangled photons, circuit drivers and receivers. These consumers have been compared with the classical method by deriving power models for both methods. Based on the latter, and the UEs data rates, the energy efficiency have been compared by assuming the network is serving an amount of UEs aimed to move from one cell to another.

As far as the authors know, there is no similar work that tackled reducing the delay and power consumption by using the quantum method that is adapted within the mobile network.

The rest of the paper has been organized as follows. In Section II, the related works are summarized. In Section III, we have discussed the quantum fundamentals. In addition, in Section IV, we discussed the adaptation of quantum and cloud networks. The quantum handover performance is included in Section V. Finally, we focuses on the system evaluation by examining the classical delay, quantum delay, and energy efficiency.

II. RELATED WORKS

In [18], the adaptive cost that is originated from using quantum technology in classical communication has been discussed. The cluster head selection policy is solved by using the quantum approximate optimization algorithm to achieve an energy-efficient network.

In [19], the technical aspects of quantum computer based systems such as quantum memory, quantum gate, quantum control, and quantum error correction have been introduced. The entropy of quantum channels is studied in [20]. In [21], a quantum repeater was proposed to reduce network errors while evaluating the channel capacity. In [22], a satellite has been utilised to exchange entangled photons over one hundreds of kilometers channel long . In [23], as well as in [24], models are proposed to provide a solution by using entanglement security in quantum internet networks. Moreover, the authors of [25] have proposed a multi-layer process for optimising internet based quantum networks. This technology limits the processing time of the node's quantum memory, improves the connection performance, and reduces the amount of signaling. In [26], entanglement theory is used to protect network security by enabling quantum based key distribution. Following, the researchers in [27] have used the free space to distribute entangled photons over 13.5 km experimentally. The authors showed that these photons can always survive such a long distance. Subsequently, classical data is transmitted between parts through quantum teleportation channels [28]. In [29], the progressive bits are encoded using optical fiber by using a transmission connection, and the transmitted photonic array is used to improve the final network throughput. The author of [30] showed that traditional data and quantum data could be transmitted without using the photon invisible sound transmission coefficient to divide the reference signal. In [31], the authors have distributed high-dimensional quantum states over 2 km of multi core fiber. They demonstrated how their implementation would benefit from quantum bits' advantages, e.g., their higher noise resilience and greater information power. However, in [32], it was found that the communication costs in quantum networks are at least twice the cost of traditional networks using the same number of parameters. Furthermore, Table 1 provides updated protocols and improvements related to quantum communications.

TABLE 1. Related works within quantum communications and quantum computing.

Method	Applications	Research
quantum networking	wireless communications	[33]
private quantum	mobile communications	[34]
super-dense coding	decoding the quantum bit	[35]
non-cloning	ciphering	[36]
compression	coding	[37]
entanglement	quantum broadcasting	[38]
optical communications	communication protocols	[39]
key distribution	quantum security	[39]
unique numbers generation	quantum coding	[40]
channel capacity	quantum channels	[41]
concentrating	entanglement transformations	[42]

III. QUANTUM FUNDAMENTALS

A. QUANTUM BITS

The classical analogue bit in quantum mechanics is called a qubit, represented by Θ and a two-state system, a superposition of 0 and 1 at the same time. Any two-state system can encode qubits, such as spin of electrons, nuclear rotation, and photon polarization. However, photons are ideal for naming qubits in communications domain because photons maintain recoverable interactions among other particles. As a result, qubits can maintain their polarization state for a long time [43].

Hence, the mathematical representation of the qubit is: $|\Theta\rangle = \alpha\,|0\rangle + \beta\,|1\rangle$ where α and β are the probability amplitudes of the photon to be 0 and 1, that is equal to $\sqrt{2}$, respectively. The probability of outcome 0 is calculated by squaring its corresponding probability amplitude $|\alpha|^2 = 1/2$. Similarly with the outcome 1, resulted from $|\beta|^2 = 1/2$, where $|\alpha|^2$+$|\beta|^2$=1. Using the style, in terms of polarisation, the qubit can be written as $|\Theta\rangle = \alpha\,|H\rangle{+}\beta\,|V\rangle$ with half probability for the photon to outcome $|H\rangle$ or $|V\rangle$ states.

B. QUANTUM ENTANGLEMENT

There are many standalone behaviors in quantum mechanics, the most interesting of which is a quantum entanglement, or teleportation. This phenomenon causes the photon status to be passed automatically between many and remote locations [44]. A mechanism known as a spontaneous down conversion produces such correlated photons where an intense laser beam interacts non-linearly with the incident high frequency on to a nonlinear crystal. In 1935, the EPR paradox, symbolises Einstein, Podolsky and Rosen scientists, has discovered this hypothesis. Such conduct was viewed as unlikely when facts are violated, and Einstein often referred to it as spooky action at a distance because the information have been passes to the other side receiver instantly. This is because the photons' correlation takes zero time and breaks the light's speed limit by an ambiguous wave function, or called hidden variable [45]. However, this means that it is possible to pump a crystal by one classical bit and produce multiple photons [46]. In other words, it helps the transmitter to send pairs of bits using a singular classical bit, without using robust coding methods, without complicating the primary devices. Furthermore, the photons are secured automatically, and no further strategies for protection are needed; where each generated photon may hold two states at the same time, in contrary to classical bits, such as vertical and horizontal states. At the reception side, the two states photon decay and one of the two conditions is obtained by a polariser. The twin photon automatically collapses to its orthogonal condition, which causes the knowledge about the second state to be understood from the first one. For instance, when two entangled photons are generated, if the first receiver detects horizontal, the second receiver shall detect vertical, and vice versa, following the famous Bell states [47]. If more than two photons are generated, their polarisation angle can be distributed from 0 to 360 while keeping less orthogonality properties.

C. QUANTUM CLOUD NETWORKS

A laser can be derived by the classical bits of a specific classical UE; the laser then pumps the nonlinear crystal, producing the entangled photons. These photons are transmitted to the RRHs where this UE resides, using an optical fiber or wireless channel. Subsequently, the photons are detected at the RRHs, each with specific photon state, and the classical bits are recovered. As a result, this process has duplicated the classical bit to several bits at no additional expenses. When the UE travels to the neighboring RRH, the information is served immediately using these redundant bits (already sent to the destination RRH at the time of photons generation). The need for an X2-AP framework protocol for handover signalling then is mitigated.

The legacy problem of the cloud radio access network is thet it allows the UE to connect to the cloud center so as its data to be processed, then these data are sent to the UE through its RRH. The network delay is consequently increased since the distances to the UEs are increased. Moreover, further delay will be caused due to the control plane, mostly handover process. If the handover takes place, multiple packets will be exchanged between UE, destination

BBU, source BBU, serving and packets gateways, and mobility management units, this causes the cost of delay and power consumption to be at high levels. Therefore, the proposed approach uses entangled photons as direct transmission signals between the associated handover units to reduce these costs. This study however, utilises the hidden between the interconnected photons where changing the polarization state of one photon is directly affecting the others.

D. QUANTUM HANDOVER

The classical handover procedure can be described, as follows:

i. The UE receives a power level from a target RRHs and reports these to its existing RRH (source RRH), the UE uses RRC control signals for all possible target RRHs.
ii. The target RRH is selected to be the based on which one the UE receives higher power from.
iii. The source RRH sends a handover request to target RRH to plan the handover method with the required information (e.g., RRH detail, UE context, resource blocks mapping).
iv. The target RRH shall track the availability of necessary resource, and sends a confirmation to the former RRH.
v. In the meantime, the UE will aim to access the target RRH, transmitting the message to its target RRH 'RRC Link Setup Complete.' The latter then sends to the MME a message telling the UE that its RRH has been updated.
vi. The MME sends UE details and the current position to the SGW and PGW. Subsequently, the SGW sends downlink packets to the target RRH rather than the source RRH and recognizes the MME.
vii. Finally, the target RRH calls on the source RRH to finally release the UE. This led to the end of the transition process.

It is worth mentioning that the handover process in the cloud architecture happens in the cloud center, where the source and target BBUs are all together in the same place. In contrast, the quantum handover happens amongst remote parties. Below is some of the features for the quantum method.

i Let us assume BBU1 serving RRH1 and BBU2 serving RRH2. While the RRH1 UE transferred to RRH2, after all, it serving (BBU1) could still be used, like photons (converted into conventional bits at RRH) are rendered from one bit of UE information. Again, The UE data is then doubled and directed to RRH2, saving power and time in the pool.
ii This means the UE can be moved to target RRH2 and still be served by BBU1. This matter is very important as the target RRH is not always ready for the handover, not supported by X2-AP or does not own the required resources on time. However, the UE's requirement for the status transfer is not requested to provide additional control signals with the target BBU.
iii It provides free channels to transfer photons between RRHs and Cloud Centers using optical fibers.
iv The study has shown that the X2-AP protocol faces a significant loss in classical communications, which can be described as unreliable and scalable [48].
v Classically, the X2-AP interface can be upgraded to the latest in both BBUs, which is tedious and costly [49]. Thus, entanglement can be a legitimate solution.
vi The transition process has begun even before the transfer being sought due to sparing more than entangled photons.
vii Some BBUs have no X2-AP interface within the network architecture traditionally; the S1 protocol is a replacement in this case. Two BBUs carry out the handover along with the MME. In this case, the interconnection approach applies to an optimal relief of X2 and S1 to carry out the switch.

IV. SYSTEM EVALUATION

In more details, the classical handover can be described in Algorithm 1:

Algorithm 1 Classic Handover

Evaluate UE position
Evaluate UE measurement, **do**
RRHs-MME (handover req)
MME-RRHt (handover req and Ack)
MME-RRHs (handover command)
RRHs-MME (Status transfer)
RRHs-SGW (forward UE data)
MME-RRHt (status transfer)
SGW-RRHt (forward UE data)
RRHt-MME (Notify handover)
MME-SGW (Modify bearer request)
SGW-MME (Modify bearer response)
MME-RRHs (Context release command)
RRHs-MME (Context release comp)

The quantum handover is relying on performing each of the steps of Algorithm 1 but utilising the photon states of the entangled photons, where $|\psi_1|$, $|\psi_2|$, $|\psi_3|$ and $|\psi_4|$ are the final photon states (after detection) of four entangled photons, as shown in Algorithm 2.

In Fig. 1, when the UE of RRH1 moves to the next RRH2, the cloud sends the UE data to all the surrounding RRHs of the UE, enabling copy-free of such data, thanks to the generation process of entangled photons. Meanwhile, if the sending eNodeB informs the MME about the handover, the former can utilise the hidden quantum channel to pass the information to the latter. Passing the information can simply be implemented by changing the polarisation of the former, the latter will change immediately at no time.

We first examined the UE position, where the UE informs the serving RRH of its RCC measurements. Once the deci-

Algorithm 2 : Quantum Handover

Evaluate UE position
Evaluate UE measurement
Trigger Entanglement, **do**
Change $|\psi_1|$ SeNodeB- receive $|\psi_2|$ MME
Change MME $|\psi_2|$-receive TenodeB $|\psi_3|$(handover req and Ack)
MME $|\psi_2|$-SeNodeB $|\psi_1|$ (handover command)
MME $|\psi_2|$-SeNodeB $|\psi_1|$(handover command)
SeNodeB $|\psi_1|$-MME $|\psi_2|$ (Status transfer)
SeNodeB$|\psi_1|$-SGW $|\psi_4|$(forward UE data)
MME-RRHt (status transfer)
SGW $|\psi_4|$-RRHt $|\psi_3|$(forward UE data)
RRHt-MME (Notify handover)
MME$|\psi_2|$-SGW $|\psi_4|$(Modify bearer request)
SGW $|\psi_4|$-MME $|\psi_2|$(Modify bearer response)
MME$|\psi_2|$-RRHs $|\psi_1|$(Context release command)
RRHs $|\psi_1|$-MME $|\psi_2|$ (Context release comp)

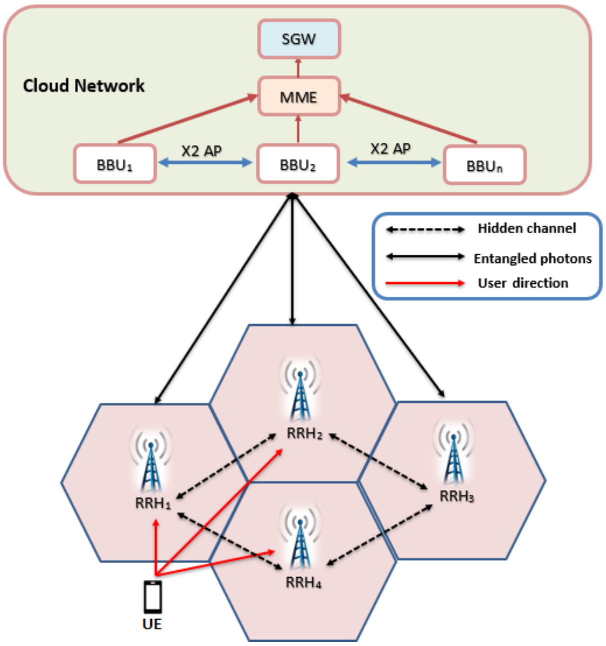


FIGURE 1. Quantum handover process architecture.

sion is made, several connections has to be made to finally release the UE to the target RRH, as shown in Algorithm (1). After receiving the measurement of the UE, the serving RRH (RRHs) sends communicates with the MME to inform about the handover process, the MME in turn, informs the target RRH and finds if it has the required resources, with handover request and acknowledgment signals. Then the MME commands the RRHs of the handover.The later sends the UE status to the MME and UE data to the SGW to establish the new channel for the UE. Then more communications to be done amongst the participants to finally release the UE. In the quantum handover, presented in the Algorithm 2. In the latter, the classical signals are replaced with state changing procedure. The advantage of such method is the time reduction. The polarisation of the states, once it is perturbed, the other correlated states are all responded and be collapsed. This situation can happen amongst whatever units that participate in the handover procedure.

A. CLASSICAL DELAY

The time delay of this process can be analysed by evaluating the time of each sub-control operation due to the handover process. Although, the classical handover timing diagram depends on the latest technologies related to manufacturing the servers responsible for processing, manipulating, and sending the necessary control signals. However, the overall timing for the classical handover procedure is taking a remarkable cost that may cause of the outage in the UE's connection, loss of power, increased delay and lack of network reliability. The delay is analysed in many steps before knowing the differences between classical and quantum methods. We have denoted the MME with m, sending RRH with s, target RRH with t, and gateway with g. That is D_{sm} means the delay between the sending RRH and MME, D_{mt}, denote the delay between the MME and target RRH. Moreover, the delay between the MME and serving gateway is denoted by D_{mg}, and so on.

The overall delay of the classical method is the combination of processing delay and channel distance delay. The processing delay in the classical handover is known in the range of several milliseconds. If the handover request operation is evaluated, the delay of sending, channel and receiving will be evaluated, as follows:

$$D_{sm} = D_s^p + d_{sm} + D_m^p \tag{1}$$

where D_s^p represents the processing delay of the sending RRH, d_{sm} is the distance delay between the sending RRH and the MME, and D_m^p is the processing delay of the MME. Moreover, the delay of the handover request between the MME and target RRH (D_{mt}) is calculated as:

$$D_{mt} = D_m^p + d_{mt} + D_t^p \tag{2}$$

where D_t^p is the processing delay of the target RRH, and d_{mt} denotes the distance between them. This procedure will continue until the UE is finally released.

B. QUANTUM DELAY

In the quantum case, there also be a delay that is originated from the process of generating the entangled photons. The delay in the quantum case mostly happens in the circuit responsible for synchronising, elaborating and measuring the photons states amongst the different RRHs. In addition, there is another delay that happens when the tagged RRH informs other RRHs about its measuring state, classically, so the other RRHs detect whether their collapse states are correct or not. Accordingly, the RRHs error-correcting the received states, quantum wise.

The first delay consumer unit is the polarisation measurement at the receiving side, where the sending RRH measurs its polarisation due receiving a classical signal revealing the state of the sending RRH. Subsequently, the receiving RRH examined if its final state was correct or not. If not, correcting this state is mandatory using quantum error correction by re-sending the entangled photon. Suppose the classical signal being transmitted at the same time of measuring the state. We have denoted the delay due to the classical channel at each unit by d_c, this delay will be for all participating units. However, the delay of receiving the entangled photons is divided by two parts: the first is the delay of receiving detector at each unit, or called response time, denoted by D_{res}, second, the delay of translating this photon to a classical bit, denoted by D^p_{dri}. Hence, the total delay in the quantum case is summarised as follows:

$$D_{qd} = D_{res} + d_c + D^p_{dri} \tag{3}$$

C. QUANTUM CONSUMPTION

We have assumed the total power consumption of the network, denoted as P_{QT} included two main parts: the traditional power consumption and the quantum. The power consumption of the traditional cloud is $P_{traditional}$, and the power consumption of quantum side is $P_{quantum}$.

$$P_{QT} = P_{quantum} + P_{traditional} \tag{4}$$

The former mainly contains the BBUs and the RRHs. The BBUs are responsible for processing the base band signals and the arrived/transmitted packets of the UEs. The server power consumption is denoted as P_{server}, where a group of servers assemble the cloud center. There are other consumptions within the cloud such as the power overhead, and fiber losses. It is worth mentioning that the server consumption itself is not a fixed value, it is directly proportional to the number of processed packets, i.e. the bandwidth (BW). The change in its consumption ∂P_{server} to the change of the bandwidth ∂BW is equivalent to a constant, as follow:

$$\frac{\partial P_{server}}{\partial BW} = \alpha P_{server} \tag{5}$$

when solving this equation, it produces:

$$P_{server}(BW) = P^{initial}_{server} \exp^{\alpha BW} \tag{6}$$

The server power consumption as a function of the bandwidth is the initial power consumption that is affected by the constant and the bandwidth. When the is no bandwidth (no load), the server power consumption is only its initial power consumption, i.e. idle mode of operation. In addition, id we assume the total number of operating servers is C, the total servers power consumption is represented by $P^T_{servers}$. However, the cloud, as mentioned earlier, included other consumptions, that are also proportional to the total servers consumptions. These losses are summed by, AC-DC, DC-DC, and cooling power consumptions. Generally, these consumptions are due to power losses. For example, the AC power is not efficiently converted to the DC power (required for operating the servers). As such, the DC power is not perfectly converted to the required value of DC power (required to each unit in the server and the cloud). Hence, we have assumed these consumption as power losses. The AC-DC is represented by σ_{AC}, the DC-DC consumption is denoted by σ_{DC}, and cooling consumption is represented by the factor $\sigma_{cooling}$. Subsequently, the cloud power consumption is formulated as follows:

$$P_{traditional} = \frac{P^T_{servers}}{\sigma_{AC} \times \sigma_{DC} \times \sigma_{cooling}} \tag{7}$$

And this is valid for only one cloud. If there is more than one cloud, the above formula is repeated as many as the cloud centers.

The other part of the cloud consumption is the RRH, we have denoted this consumption as (P_{RRH}). The power consumption of this unit contains the radio unit (P_{RADIO}), power amplifier (P_{AMP}). This unit is also submitted to the overhead losses, but not the cooling, as its consumption is low and does not requires cooling.

$$P_{RRH} = \frac{P_{AMP} + P_{RADIO}}{(\alpha_{AC})(\alpha_{DC})} \tag{8}$$

Where $P_{AMP} = P^t_{r,ue}/\sigma_{pa}$ is formulated as the transmitted signal to the UEs $P_{rrh,ue}$ to its efficiency η_{AMP}. Hence, the total power consumption of the traditional part is updated to the following, as pursues:

$$P_{traditional} = \frac{P^T_{servers}}{\sigma_{AC} \times \sigma_{DC} \times \sigma_{cooling}} + \frac{P_{AMP} + P_{RADIO}}{(\alpha_{AC})(\alpha_{DC})} \tag{9}$$

The quantum part of the network can also be divided into two parts, the first part is the quantum cloud part, denoted as P_{QC}. The second part is the quantum RRH part, denoted as P_{QR}. In the former, there are several components that are required to perform the necessary quantum computations. It is to be noted that the uplink communications is always classical, and the downlink is quantum. This required a laser in the cloud center to pump the BBU crystal that generates the entangled photons and send them to the RRHs. The uplink procedure can be done classically and no need for the detector in the cloud. At the RRH, it is required several units, a detector to receive the photon, a driving circuit, and a polarisation synchroniser. Hence, the power consumption of the quantum cloud P_{QC} is equivalent to $P_{QC} = P_{laser}$, while the P_{QR} can be given as follow:

$$P_{QR} = P_{det} + P_{driver} + P_{synch} \tag{10}$$

Hence, the quantum power consumption can be summed as

$$P_{quantum} = P_{QR} + P_{QC} \tag{11}$$

D. ENERGY EFFICIENCY

Among the different network metrics, energy efficiency is an important metric to evaluate, considering power consumption as a parameter. In this work, the energy efficiency gain is evaluated to show the importance of the proposed method. The EE can be defined as the transmitted data rate (bits/s or bps) to the power consumption (Watt). This means how much data rate is transmitted when consuming one Watt of power, i.e. (bps/W). As a matter of the fact, each classical protocol happens at different bandwidth than the data plane bandwidth, in this work, we have assumed the bandwidth as 10 MHz.

$$CRate = \sum_{m=1}^{M} BW\ log_2(1 + \frac{P^T_{c,m} H_m\ r_m}{AWGN + I_m}) \tag{12}$$

where $CRate$ denotes the classical data rate, M is the total number of RRHs, $AWGN$ is the additive white Gaussian noise, $P^t_{c,m}$ is the transmitted power the $m-th$ antenna, and H_m is the channel gain of the RRH m. The $r_m = d^{\alpha}_m$ represents the path loss, d_m is the distance of the RRH m to the target RRH. α is path loss exponent, I_m denotes the interference from other RRHs up on the tagged channel m. Subsequently, the EE formula can be produced for the classical network as follows:

$$EE_{traditional} = \frac{CRate}{P_{traditional}} \tag{13}$$

In the quantum case, the data rate is already embedded within the entanglement quantum channel that happens instantly without classical considerations. However, for the sake of comparison, the bandwidth of the laser can be considered as the required bandwidth for the quantum case, as follows:

$$QRate = \sum_{m=1}^{M} BW\ log_2(1 + \frac{P^T_{q,m} Pr(m, M)}{Loss_m}) \tag{14}$$

Where

$$Pr(m, M) = \int d\lambda \rho(\lambda) pa_1(m, \lambda) pa_n(M, \lambda) \tag{15}$$

denotes the coincidence probability amongst the measurements of RRH m and other RRHs M, $pa_1(m, \lambda)$ is the detection probability of particle a in the direction of RRH m, sharing the same value of the hidden variable λ. Subsequently, $pa_n(M, \lambda)$ is the detection probability of particle a_n in the direction of other RRHs M, a_n is the indication of particle number n, and $n \in 1 : N$ denotes the total number of entangled photons. In addition, $\rho(\lambda)$ represents the probability of the produced photon state. $P^T_{q,m}$ represents the transmitted power of the laser of the RRH m, $Loss_m$ denotes the network's loss budget on the RRH m, which includes number of fiber splices, connectors, dispersion and distance. Subsequently, the EE can be calculated as:

$$EE_{quantum} = \frac{QRate}{P_{quantum}} \tag{16}$$

E. SYSTEM COMPLEXITY

The complexity of the proposed methods relies upon the continuous moving UEs. The proposed method is aimed to surround the moving UE with entangled photons so as its data plane constantly be available and the hidden channels can operate. When the UE moves to cells that are not within the entanglement zone (where the fisrt set of photons are distributed), this case causes the UE to shift to the classical handover. This problem can be realised by predicting the direction of the UE and providing the extra cells with the entangled photons. Another solution is to provide more entangled photons in all directions around the UE. Another problem is that the RRHs are practically not uniformly distributed, based on hexagonal or circular shapes. Our work used the Poison point process to deploy the RRHs, a more practical-oriented paradigm that conveys real-time cell shapes. This matter requires an optimisation process to predict which RRH is closer to the UE and represents its surrounding cell. However, the more entangled photons to be used, the more cells can participate in the UE perimeter. Non the less, this process must continue to operate as long as the UE moves, providing a collar coverage for the next direction of the UE. However, generating more entangled photons is more complex than fewer photons, so the states of the generated photons become more challenging to distinguish. This matter requires more caring on the receiving side so as the tagged state will be purified.

V. RESULTS

There are participant units involved in the handover process, these are source RRH, target RRH, MME and SGW, we have assumed the distance of the source RRH to the MME 100 km, the distance of MME to target RRH is 100 km, the distance between source RRH to SGW is 100 km, while the distance of SGW to target RRH is 100 and finally, the distance of MME to seving GW is 50 km. These five distances have been suggested to show the existed connection amongst these parties no matter how many repetitive connections happen during the handover process. These distances are used to produce the channel delay of these wireless links. This wireless link can easily be replaced with optical fiber channels to compare and show another results of this work. In addition, the processing delay of the source RRH is assumed to be 3 ms, the target RRH is 3 ms , the MME unit is 15 ms and SGW is 5 ms. These has been added to the processing delay to produce the final delay that is

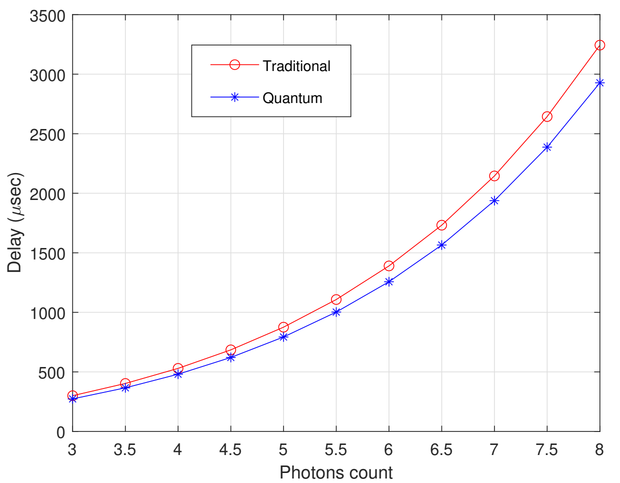


FIGURE 2. Latency of the networks, quantum and traditional with respect to the number of entangled photons.

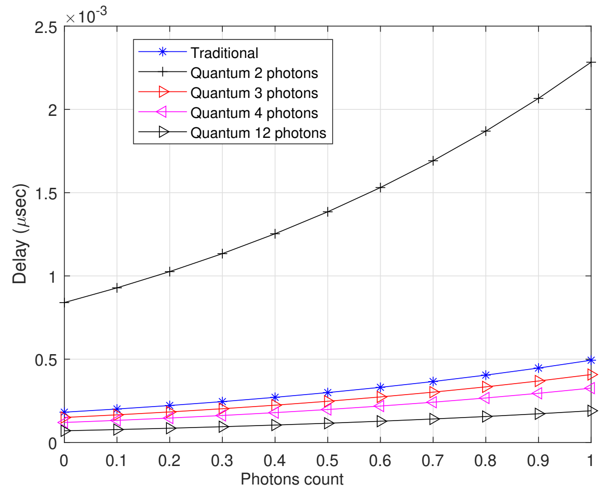


FIGURE 3. Latency of the networks, quantum and traditional showing the effect of delay gain when using different number of photons.

shown in Fig 2. In the two-photon scenario, more delay will be produced than the three or four photon cases due to more ping-pong signalling required. This means the more photons to be generated, the more efficient the system will perform. Note that when calculating the final delay of the source RRH-MME link, the processing delay in the source RRH occurs 5 times, so does the MME, as in Algorithm 1. Hence, the total delay of this link is equivalent to the link delay, in addition to 5 times the processing delay. Similarly with other links, such as MME-target RRH shown in Fig 3. Subsequently, the total delay of the traditional case is produced by jointly adding the delays of all links. The delay in the quantum case is also produced the same way, the processing delay of the laser, detector and the driving units, as shown in Table 2, have been jointly added to the total quantum delay.

TABLE 2. Model Parameters

Factor	Value	Unit	Factor	Value	Unit
D_s^p	3	ms	d_{sm}	5	ms
D_m^p	15	ms	d_{mt}	5	ms
D_t^p	3	ms	D_{res}	1	-
d_c	1	-	D_{dri}^p	1	-
D_{dri}^p	1	-	$P_{servers}^T$	0.01	W
σ_{AC}	0.9	-	σ_{DC}	0.91	-
$\sigma_{cooling}$	0.92	-	P_{AMP}	29.7	W
P_{RADIO}	12.9	W	α_{AC}	0.8	-
α_{DC}	0.8	-	$P_{\det}$	1	W
P_{driver}	1	W	P_{synch}	1	W
BW	10	MHz	H	1	-
$AWGN$	-10	$\frac{dB}{Hz}$	P_q^T	43	dBm
$Loss$	-3	dB			

In Fig 4, the power consumption has been presented with respect to the number of UEs. We have assumed the number of BBUs is 20, RRHs is 50. We also assumed the worst case scenario, where the X2 protocol consumes only 10% of the power consumption of the classical server, this amount has

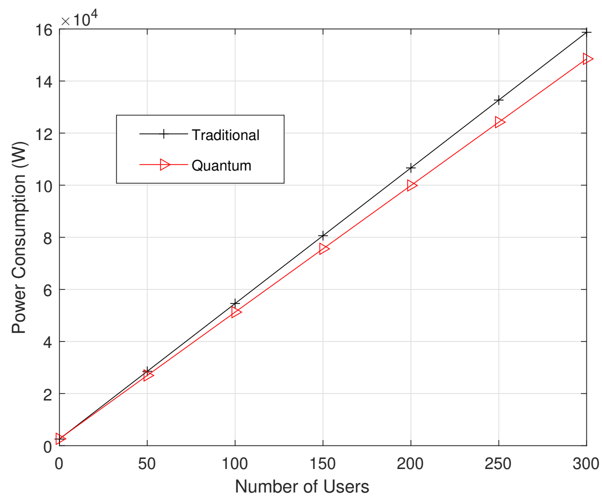


FIGURE 4. Power consumption with respect to the number of UEs, when the X2-AP protocol consumes only 10% of the classical server power consumption.

been deducted in the quantum case to gain such power. It shows when the number of UEs increases, the amount of power saving increases too. However, practically speaking, the network may contains thousands or million of UEs that moves constantly during the day. Hence, this saving can be further increased. In addition, Fig 5 show the power consumption of the two networks when the X2 protocol consumes 20% of the power consumption of the classical server. This case has gained more power as it reduces the amount of the classical X2 handover from the quantum case.

Later, the power consumption has been utilised to produce the energy efficiency, the average data rate was first calculated using the channel capacity formula. In the latter, the power from the RRH to the UEs was distributed based on the UEs distances to the tagged RRH, the nearest the UE to the RRH, the less received power. Additive white

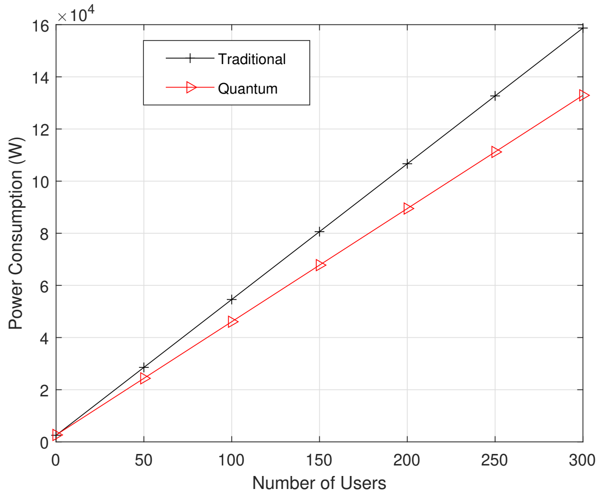


FIGURE 5. Power consumption with respect to the number of UEs, when the X2-AP protocol consumes 20% of the classical server power consumption.

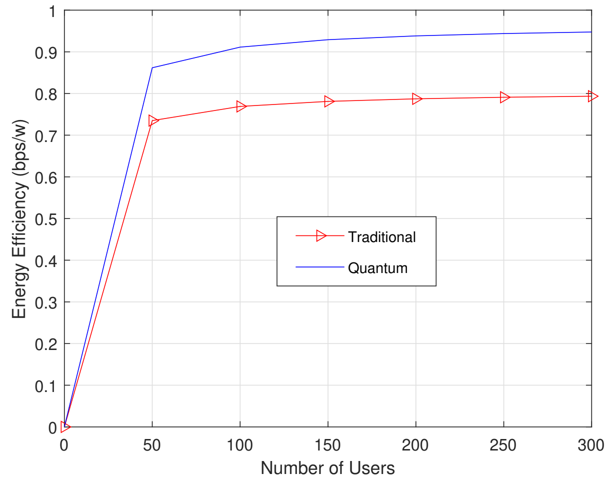


FIGURE 7. Energy efficiency with respect to the number of UEs when the power consumption is 20 %.

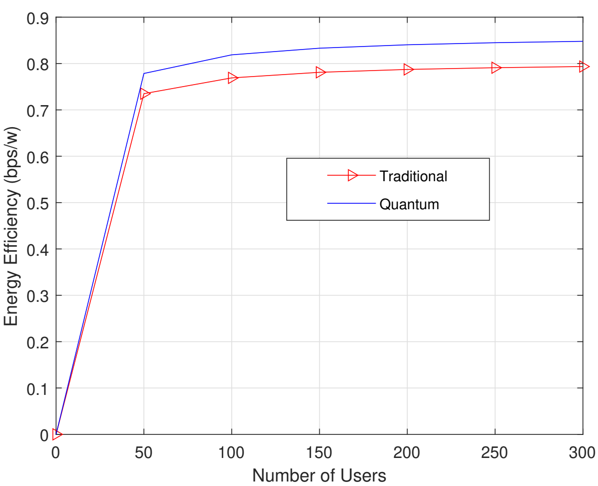


FIGURE 6. Energy efficiency with respect to the number of UEs when the power consumption is 10 %.

Gaussian noise has been suggested, the channel gain is also calculated. Moreover, Fig. 6 shows the energy efficiency of the network when the power consumption is 10% less in the server compared to the classical one. Where in case of 20%, the energy efficiency of the quantum network will be further increased. However, the energy efficiecny and the power consumption behave differently because in the former, the data rate will drive the increment of the power consumption towards exponential and linear behaviours, at the same time. First, Exponential this can happen as the UEs are still bandwidth and power hungry, which drives the average data rate to exponentially increase from zero to higher values while serving almost first 50 users in the network. After that, the scarce resources of the system urge to share the bandwidth and power transmitted amongst all the 300 UEs, which makes the system increases almost linearly while increasing the number of UE. It is worth mentioning that the number of UEs may fluctuates at each Monte-Carlo iteration as Poison point process distribution has been implemented to generate the UEs and the RRHs. Finally, the cloud center has been assumed in the center of the geographical area.

VI. CONCLUSIONS AND FUTURE WORK

This paper showed how quantum entanglement can be used in classical cellular communications to improve the performance of the X2 application (X2-AP) protocol. We have concluded that the power consumption have been decreased to approximately 20% in the quantum case compared to the traditional network by increasing the number of UEs. Similarly, the delay has decreased while increasing the number of entangled photons used to connect the RRHs and other network parties. It is worth mentioning that the delay of two photons case is more than the traditional case since there will be enlarged number of background communications and synchronisation. However, by increasing the number of photons to four and more, the delay decreases compared to the traditional network by about 40%. Finally, the energy efficiency increases in the quantum case by decreasing the power consumption by about 10% as the number of UEs increases.

In the future, the quantum entanglement can be used not only amongst the RRHs, but amongst the RRHs and the cloud centre. This results in updating the cloud, MME and SGW without time cost. It was expected that this method can further improve quality of service regarding the time. However, the concurrent trade-offs have to be analysed regarding the power consumption and system complexity. The latter can be realized by the means of artificial intelligence and quantum computing algorithms to control the procedure of photons transmission, receiving, purifying the photon polarization's states, updating the handover participants and error correcting the undetected photons. Furthermore, increasing the performance of the proposed method to cover RRHs that are not connected to the same cloud center, this may impose additional complexity. The latter is represented by initiating more channel for synchronising and tracking the UEs.

REFERENCES

[1] A. Mohammad and L. Chunlin, "An optimized cloudlet scheduling based method for tablets and mobile phones," in 2021 International Conference on Computer Technology and Media Convergence Design (CTMCD). IEEE, 2021, pp. 248–252.

[2] D. Han, W. Chen, and Y. Fang, "Joint channel and queue aware scheduling for latency sensitive mobile edge computing with power constraints," IEEE Transactions on Wireless Communications, vol. 19, no. 6, pp. 3938–3951, 2020.

[3] S. Ranjan, P. Chaporkar, P. Jha, and A. Karandikar, "Backhaul-aware cell selection policies in 5g iab networks," in 2021 IEEE Wireless Communications and Networking Conference (WCNC). IEEE, 2021, pp. 1–6.

[4] M. Z. Chowdhury, M. Shahjalal, S. Ahmed, and Y. M. Jang, "6g wireless communication systems: Applications, requirements, technologies, challenges, and research directions," IEEE Open Journal of the Communications Society, vol. 1, pp. 957–975, 2020.

[5] R. S. Alhumaima, M. Khan, and H. S. Al-Raweshidy, "Component and parameterised power model for cloud radio access network," IET Communications, vol. 10, no. 7, pp. 745–752, 2016.

[6] R. S. Alhumaima and H. S. Al-Raweshidy, "Modelling the power consumption and trade-offs of virtualised cloud radio access networks," IET Communications, vol. 11, no. 7, pp. 1158–1164, 2017.

[7] B. A. A. Nunes, M. Mendonca, X.-N. Nguyen, K. Obraczka, and T. Turletti, "A survey of software-defined networking: Past, present, and future of programmable networks," IEEE Communications surveys & tutorials, vol. 16, no. 3, pp. 1617–1634, 2014.

[8] S. Bassoy, M. Jaber, M. A. Imran, and P. Xiao, "Load aware self-organising user-centric dynamic comp clustering for 5g networks," IEEE Access, vol. 4, pp. 2895–2906, 2016.

[9] X. Yang, Y. Wang, D. Zhang, and L. Cuthbert, "Resource allocation in lte ofdma systems using genetic algorithm and semi-smart antennas," in 2010 IEEE Wireless Communication and Networking Conference. IEEE, 2010, pp. 1–6.

[10] M. Peng, K. Zhang, J. Jiang, J. Wang, and W. Wang, "Energy-efficient resource assignment and power allocation in heterogeneous cloud radio access networks," IEEE Transactions on Vehicular Technology, vol. 64, no. 11, pp. 5275–5287, 2014.

[11] M. Kim, S. Kasi, P. A. Lott, D. Venturelli, J. Kaewell, and K. Jamieson, "Heuristic quantum optimization for 6g wireless communications," IEEE Network, vol. 35, no. 4, pp. 8–15, 2021.

[12] Y.-W. Cho, G. Campbell, J. Everett, J. Bernu, D. Higginbottom, M. Cao, J. Geng, N. Robins, P. Lam, and B. Buchler, "Highly efficient and long-lived optical quantum memory with cold atoms," in 2017 Conference on Lasers and Electro-Optics (CLEO). IEEE, 2017, pp. 1–2.

[13] S. Wijesekera, X. Huang, and D. Sharma, "Multi-agent based approach for quantum key distribution in wifi networks," in KES International Symposium on Agent and Multi-Agent Systems: Technologies and Applications. Springer, 2009, pp. 293–303.

[14] T. Nagata, R. Okamoto, J. L. O'brien, K. Sasaki, and S. Takeuchi, "Beating the standard quantum limit with four-entangled photons," Science, vol. 316, no. 5825, pp. 726–729, 2007.

[15] J. M. Gambetta, J. M. Chow, and M. Steffen, "Building logical qubits in a superconducting quantum computing system," npj Quantum Information, vol. 3, no. 1, pp. 1–7, 2017.

[16] B. Fedrici, L. Ngah, O. Alibart, F. Kaiser, L. Labonté, V. D'Auria, and S. Tanzilli, "All-optical synchronization for quantum communication networks," in 2017 19th International Conference on Transparent Optical Networks (ICTON). IEEE, 2017, pp. 1–3.

[17] A. Chinnappan and R. Balasubramanian, "Complexity–consistency trade-off in multi-attribute decision making for vertical handover in heterogeneous wireless networks," IET Networks, vol. 5, no. 1, pp. 13–21, 2016.

[18] J. Choi, S. Oh, and J. Kim, "Energy-efficient cluster head selection via quantum approximate optimization," Electronics, vol. 9, no. 10, p. 1669, 2020.

[19] M. Erhard, M. Krenn, and A. Zeilinger, "Advances in high-dimensional quantum entanglement," Nature Reviews Physics, vol. 2, no. 7, pp. 365–381, 2020.

[20] H.-J. Briegel, W. Dür, J. I. Cirac, and P. Zoller, "Quantum repeaters: the role of imperfect local operations in quantum communication," Physical Review Letters, vol. 81, no. 26, p. 5932, 1998.

[21] M. Aspelmeyer, T. Jennewein, M. Pfennigbauer, W. R. Leeb, and A. Zeilinger, "Long-distance quantum communication with entangled photons using satellites," IEEE Journal of Selected Topics in Quantum Electronics, vol. 9, no. 6, pp. 1541–1551, 2003.

[22] L. Gyongyosi and S. Imre, "Distributed quantum computation for near-term quantum environments," in Quantum Information Science, Sensing, and Computation XIII, vol. 11726. International Society for Optics and Photonics, 2021, p. 117260I.

[23] I. P. Christov, "Spatial entanglement of fermions in one-dimensional quantum dots," Entropy, vol. 23, no. 7, p. 868, 2021.

[24] M. Chehimi and W. Saad, "Entanglement rate optimization in heterogeneous quantum communication networks," arXiv preprint arXiv:2105.14507, 2021.

[25] K. Boström and T. Felbinger, "Deterministic secure direct communication using entanglement," Physical Review Letters, vol. 89, no. 18, p. 187902, 2002.

[26] C.-Z. Peng, T. Yang, X.-H. Bao, J. Zhang, X.-M. Jin, F.-Y. Feng, B. Yang, J. Yang, J. Yin, Q. Zhang et al., "Experimental free-space distribution of entangled photon pairs over 13 km: towards satellite-based global quantum communication," Physical review letters, vol. 94, no. 15, p. 150501, 2005.

[27] M.-H. Hsieh and M. M. Wilde, "Entanglement-assisted communication of classical and quantum information," IEEE Transactions on Information Theory, vol. 56, no. 9, pp. 4682–4704, 2010.

[28] K. Banaszek, A. Dragan, W. Wasilewski, and C. Radzewicz, "Experimental demonstration of entanglement-enhanced classical communication over a quantum channel with correlated noise," Physical review letters, vol. 92, no. 25, p. 257901, 2004.

[29] N. Min, J. Jin-ya, and L. Xiao-hui, "A novel optimum quantum states entanglement multiplexing and relay scheme for land quantum mobile communication," Acta Photonica Sinica, vol. 40, no. 5, p. 774, 2011.

[30] S. D. Bartlett, T. Rudolph, and R. W. Spekkens, "Classical and quantum communication without a shared reference frame," Physical review letters, vol. 91, no. 2, p. 027901, 2003.

[31] B. Da Lio, D. Bacco, D. Cozzolino, N. Biagi, T. N. Arge, E. Larsen, K. Rottwitt, Y. Ding, A. Zavatta, and L. K. Oxenløwe, "Stable transmission of high-dimensional quantum states over a 2-km multicore fiber," IEEE Journal of Selected Topics in Quantum Electronics, vol. 26, no. 4, pp. 1–8, 2019.

[32] Y. Yang, G. Chiribella, and M. Hayashi, "Communication cost of quantum processes," IEEE Journal on Selected Areas in Information Theory, vol. 1, no. 2, pp. 387–400, 2020.

[33] S. Santra and V. S. Malinovsky, "Quantum networking with short-range entanglement assistance," Physical Review A, vol. 103, no. 1, p. 012407, 2021.

[34] M. Bérces and S. Imre, "Extension and analysis of modified superdense-coding in multi-user environment," in 2015 IEEE 19th International Conference on Intelligent Engineering Systems (INES). IEEE, 2015, pp. 291–294.

[35] I. B. Djordjevic, "Integrated optics modules based proposal for quantum information processing, teleportation, qkd, and quantum error correction employing photon angular momentum," IEEE Photonics Journal, vol. 8, no. 1, pp. 1–12, 2016.

[36] M. A. Nielsen, "Conditions for a class of entanglement transformations," Physical Review Letters, vol. 83, no. 2, p. 436, 1999.

[37] S. Imre and F. Balazs, Quantum computing and communications. Wiley Online Library, 2005.

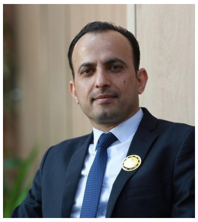
[38] B. Schumacher and M. A. Nielsen, "Quantum data processing and error correction," Physical Review A, vol. 54, no. 4, p. 2629, 1996.

[39] M. Hayashi and K. Matsumoto, "Variable length universal entanglement concentration by local operations and its application to teleportation and dense coding," arXiv preprint quant-ph/0109028, 2001.

[40] J. Li, J. Xiong, Q. Zhang, L. Zhong, Y. Zhou, J. Li, and X. Lu, "A one-time pad encryption method combining full-phase image encryption and hiding," Journal Of Optics, vol. 19, no. 8, p. 085701, 2017.

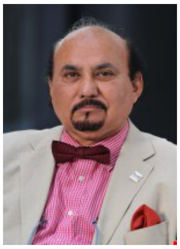
[41] J. G. Rarity, P. Owens, and P. Tapster, "Quantum random-number generation and key sharing," Journal of Modern Optics, vol. 41, no. 12, pp. 2435–2444, 1994.

[42] V. Giovannetti, A. S. Holevo, S. Lloyd, and L. Maccone, "Generalized minimal output entropy conjecture for one-mode gaussian channels: definitions and some exact results," Journal of Physics A: Mathematical and Theoretical, vol. 43, no. 41, p. 415305, 2010.
[43] P. B. Shea, E. C. Folk, D. J. Ewing, and J. J. Talvacchio, "Quantum bits and method of forming the same," May 31 2016, uS Patent 9,355,362.
[44] M. B. Plenio and S. S. Virmani, "An introduction to entanglement theory," Quantum information and coherence, pp. 173–209, 2014.
[45] P. G. Kwiat, K. Mattle, H. Weinfurter, A. Zeilinger, A. V. Sergienko, and Y. Shih, "New high-intensity source of polarization-entangled photon pairs," Physical Review Letters, vol. 75, no. 24, p. 4337, 1995.
[46] D. Huber, M. Reindl, Y. Huo, H. Huang, J. S. Wildmann, O. G. Schmidt, A. Rastelli, and R. Trotta, "Highly indistinguishable and strongly entangled photons from symmetric gaas quantum dots," Nature communications, vol. 8, no. 1, pp. 1–7, 2017.
[47] X.-L. Wang, L.-K. Chen, W. Li, H.-L. Huang, C. Liu, C. Chen, Y.-H. Luo, Z.-E. Su, D. Wu, Z.-D. Li et al., "Experimental ten-photon entanglement," Physical review letters, vol. 117, no. 21, p. 210502, 2016.
[48] X. Dong and H. Wang, "Enhanced corrections near holographic entanglement transitions: a chaotic case study," Journal of High Energy Physics, vol. 2020, no. 11, pp. 1–32, 2020.
[49] P. Calabrese and J. Cardy, "Entanglement entropy and quantum field theory," Journal of Statistical Mechanics: Theory and Experiment, vol. 2004, no. 06, p. P06002, 2004.



YASSIR AL-KARAWI received a Bachelor degree in Electronics and Communications Engineering from the University of Technology, Iraq, in 2002. He worked as Engineer (2006-2010) at Diyala University. He received an M.Sc. in Communications Engineering from the University of Technology Malaysia (UTM) in 2012. He has published several journal and conference papers. Also, He is a Member of Staff with the Department of Communications, College of Engineering, University of Diyala, Iraq. His area of interest mainly focuses on radio frequency spectrum sharing optimisations, coexistence and compatibility studies between cellular and fixed services, including next-generation systems and networks. He is currently a PhD student at Brunel University London in Uk from 2020.

RAAD S. ALHUMAIMA received the B.E. degree in communications engineering from the University of Diyala, in 2003, the M.Sc. degree was in laser/electronics and communication from the Institute of Laser for Postgraduate Studies, University of Baghdad, in 2011, and the Ph.D. degree in communications and electronics from Brunel University, London, U.K., in 2017. He has published several IET, IEEE and conference papers. He is currently a Member Staff with the Department of Communications, College of Engineering, University of Diyala, Iraq. His current research interests include next generation systems and networks, including SDN, C-RAN, NFV, and Fog-RAN, furthermore in adapting quantum and classical communications.



HAMED AL-RAWESHIDY (Senior Member, IEEE) received the B.Eng. and M.Sc. degrees from the University of Technology, Baghdad, Iraq, in 1977 and 1980, respectively, the Postgraduate Diploma degree from Glasgow University, Glasgow, U.K., in 1987, and the Ph.D. degree from Strathclyde University, Glasgow, in 1991. He was with the Space and Astronomy Research Centre, Baghdad, PerkinElmer, Waltham, MA, USA, British Telecom, London, U.K., Oxford University, Oxford, U.K., Manchester Metropolitan University, Manchester, U.K., and Kent University, Canterbury, U.K. He is currently the Director of the Wireless Network Communications Centre, Brunel University London

...