Performance Analysis of Quantum Based Cloud Radio Access Networks

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Abstract—**Quantum computing can provide a solution for many problems that classical communication networks encounter, but the knowledge gap between these two is not bridged yet. Accordingly, this paper has proposed directions, evaluations and futuristic quantum solutions to the cloud based cellular communications. This paper shows the effect of using quantum entanglement phenomena up on the classical cloud network. Particularly, using entanglement theory to decrease the enlarged signalling cost delay that the traditional cloud network faces. Through modelling the latency of both paradigms, this work promises a delay reduction when adapting quantum method into the mobile cloud networks. This paper also models the power consumption (PC) and energy efficiency of traditional and quantum based cloud networks. This work also shows, via modelling the PC, that installing a quantum based paradigm is not power costly method, rather, it shows identical power and energy efficiency figures with a possibility of improvement.**

Index Terms*—*Quantum communications, quantum cloud networks, networks, modelling, quantum channel capacity.

I. INTRODUCTION

Mobile communication networks alone consume 0.5% of the global energy consumption [1]. Because of demanding higher data rates by today's communications, the network operators deployed large number of base stations, which consume high power. Part of this power is consumed in the signalling process and control plane as more network subscribers means growing in this cost due to providing extended interfaces and protocols. Consequently, a re-design for the existing network paradigm and offering new innovative solutions can help overcoming some of these inefficiencies [2].

The increasing number of network users (UEs) demand higher bandwidth, low latency, low power consumption (PC) and efficient resources allocation. As for traditional/classical communication, enhancing these metrics run to a limit. For example, the size of manufactured transistors is now very limited, and no futuristic reduction can be achieved in Moore's law. As such, every 2 years, the number of manufactured transistor doubles in a circuit, ultimately, this law reaches its limit too. In addition, the resources allocating techniques of the available bandwidth are no longer able to enhance the spectral efficiency due to an inherently limited number resource blocks [3]. Likewise, processing delay and power consumption of a device has a limit to reach. Hence, the limitations of classical communications has to be overcome by using far more effective technology, that is, utilising quantum mechanics in classical communications, which represents a reliable and incredible method to achieve the requirements of the beyond existed generation. Quantum computing combines quantum mechanics and physical principals to solve the problems that are not easy to be solved using classical methods, such as providing secure communications and entanglement based communications [4]. Unfortunately, the research that tackles adaptation of classical and quantum communications is yet not satisfying and resides in the early stages. This is because quantum computing research itself is also incomplete. In addition, the consistency of the two systems (classical and quantum) is totally different. Although optical communications indicate several quantum properties represented by using an optical fibre as a channel, generating the photons using a laser, and receiving the light by a detector. However, one characteristic of the photon is utilised, that is wave property, which is explained in the context of classical communication. But, the photon has two properties, wave and particle simultaneously based on how the photon is manipulated and measured. Meaning, if the classical bit is represented by either 0 or 1, the quantum bit (quBit) beholds a possibility as being $|0\rangle$ and $|1\rangle$ states at the same time. It is worth noticing that the advances and applications in quantum communication have been widely spreading in the last decade, such as quantum repeating [5], quantum memory [6], quantum cryptography [7], quantum routing [8], quantum synchronisation [9], quantum relay and encoder/decoder [10], and quantum entanglement [11]. Unfortunately, these technologies was only restricted to the quantum domain without further investigation about applying/utilising quantum theory in classical domain. Accordingly, this paper contributed to offer employing quantum into classical communications below, to increase the network efficiency. Specifically, this paper discusses the cloud based quantum solutions, with the possibility to extend these solutions to the fog computing area of research. In the later, some functions are distributed to the edge devices, which makes the UEs more closer to the cell site to be served quickly. For example, in some researches, the game theory can be utilised to improve the networks' efficiency by mitigating the signalling overhead.

A. Main Contributions

1) Using quantum entanglement to reduce the signalling cost that is originated from the handover process in classical cloud communications by using quantum mechanic solutions, specifically, quantum entanglement phenomena.
2) Adapting quantum and traditional networks into a hybrid paradigm, the classical bit that is generated for a particular UE is used to drive a LASER source, the latter is used to pump a non-linear crystal, two or more entangled photons will be generated to be distributed, detected and converted back to classical bits at the remote radio heads (RRHs). The

distributed photons serve as 'ready to use' duplicated bits that are generated without additional cost. Once the UE travels to another RRH, it will be served directly by one of these bits without the need of X2AP protocol signalling.

3) Mitigating the amount of X2AP protocol signalling has reduced the time delay required to transfer the UE status from one RRH to another. To evaluate the delay, analysing and modelling both, the State of the Art (SotA) and quantum based handover delays have been achieved.

4) Mitigating the time delay might inherit an additional power cost. Hence, this paper offers a parametrised, simplified and general power consumption model that can be used to evaluate the quantum based networks.

5) Comparing the quantum based handover solution with the SotA handover process in terms of both delay and power consumption and energy efficiency. The cost of both methods are also discussed.

6) This work offers not only handover related solutions, rather, it offers a general platform that can be used to evaluate the power consumption, power gain, time delay, channel capacity and energy efficiency of the futuristic techniques that will be proposed within quantum communications field, that impact such substantial network metrics.

II. QUANTUM PRELIMINARIES

Mathematically, a quBit (θ) is denoted as $|\theta\rangle = \alpha|0\rangle + \beta|1\rangle$ or $|\theta\rangle = \frac{1}{\sqrt{2}}|0\rangle + \frac{1}{\sqrt{2}}|1\rangle$, where α and β are the probability amplitudes of the photon to be 0 or 1, respectively. This phenomenon is called a superposition. Through the possibilities α and β, it is not accessible to know if the quBit is holding the state $|0\rangle$ or $|1\rangle$ [12]. Any two states system can encode the quBit, such as nuclei's spin, electrons' spin, and photons' polarisation. Nevertheless, photons are idealistic to serve as quBits due to their low interaction with other photons which achieves low de-coherence, this means the quBit maintains its states for very long time, as well as travelling at speed of light. However, up on measuring the quBit, it collapses to one of its bases/states, i.e. either $|0\rangle$ or $|1\rangle$, the obtained basis is now specified by the complex number's absolute value. Hence, the state $|0\rangle$ is specified with the probability amplitude $|\alpha|^2$, and the state $|1\rangle$ is specified by $|\beta|^2$, as the sum of probabilities is $|\alpha|^2+|\beta|^2 = 1$ [13]. To elaborate about how the photon is dealt with and how the polarization of its states can be identified and mathematically represented, some examples are explained. The photon can be represented with probability amplitudes:

$$|\theta\rangle = \begin{bmatrix} \alpha \\ \beta \end{bmatrix}$$

where the quBit can be written as $|\theta\rangle = \alpha|a_1\rangle + \beta|a_2\rangle$, as $|a_1\rangle$ and $|a_2\rangle$ are the states of a single photon, which can be horisontal or vertical polarisation.

If a photon is passing a horizontal polariser, the probability amplitudes of this case can be represented as:

$$|-\rangle = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

which is also can be written as $1|a_1\rangle + 0|a_2\rangle$ where the first state (horizontal, $|a_1\rangle = |-\rangle$) has the probability of 1, and the probability of the second state (vertical, $|a_2\rangle = ||\rangle$) is 0, Subsequently, the vertical polarisation case can be represented by:

$$||\rangle = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

Similarly to the above elaboration, this case can be written as $0|a_1\rangle+1|a_2\rangle$ as the probability of the second state is 1, while the first state is 0. The other state that can be produced is when the vertical or horizontal light passes through a +45 degree polariser, this state can be represented as $|/\rangle = \frac{1}{\sqrt{2}}|a_1\rangle + \frac{1}{\sqrt{2}}|a_2\rangle$. The probability amplitude of this case is given as

$$|/\rangle = \begin{bmatrix} \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} \end{bmatrix}$$

which means the probability of the photon being horizontal is $(\frac{1}{\sqrt{2}})^2 = \frac{1}{2}$, and the probability of being vertical is also $(\frac{1}{\sqrt{2}})^2 = \frac{1}{2}$. In case of -45 photon polarisation state is equivalent to $|\backslash\rangle = \frac{1}{\sqrt{2}}|a_1\rangle - \frac{1}{\sqrt{2}}|a_2\rangle$. The probability amplitude of this case is given as

$$|\backslash\rangle = \begin{bmatrix} \frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{2}} \end{bmatrix}$$

which means the probability of the photon being horizontal is $(\frac{1}{\sqrt{2}})^2 = \frac{1}{2}$, and the probability of being vertical is also $(-\frac{1}{\sqrt{2}})^2 = \frac{1}{2}$. However, in the last two cases, the photon passes the 45/-45 polariser will have less intensity than the coming, it will be $cos^2(45)$ or $cos^2(-45)$, respectively. If we apply Hermitian operator up on these two cases, it will produce eigenvalues $\lambda = 1$ and $\lambda = -1$ for the two states $|/\rangle$ and $|\backslash\rangle$, respectively. Here, we simply explain what is the meaning of eigenvalue, eigenvector or Hermitian operator. If a device, for example, a vertical polariser with two light indicators green and red on the side of the polariser. When the light goes through this device, if it is vertically polarised, the green light is on, otherwise the red light is on. This light represents the eigenvalue of the experiment because there is no way to know the state of the light without measuring it. Hence, the result of the measurement is called eigenvalue (λ_n) and will be either 1 or -1, while the state of the coming photon is called eigenvector, and the polariser device represents the Hermitian operator. It is worth noting that we cannot directly measure the state of the photon, rather we have to look at the result of the measurement, i.e. λ_n, that is the Hermitian of a state (a_n).

$$H|a_n\rangle = \lambda_n|a_n\rangle \tag{1}$$

we will simplify this formula by giving an example when a measurement is performed on a specific state, presumably, state of horizontal polarisation of a photon. The Hermitian matrix (H) can be given as [14]:

$$H = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$$

when applying formula (1) on the ($-$) state, i.e. $H|-\rangle = \lambda|-\rangle$, it produces

$$\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \end{pmatrix} = +1 \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

Here we notice that the two arrays that represents the horizontal states are identical for both sides of the equation, concurrent with an eigenvalue of ($\lambda = +1$), which means the coming horizontal light fully passes the horizontal polariser. On the other side, the Hermitian operator of vertical state, i.e. $H||\rangle = \lambda||\rangle$ as follows:

$$\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \begin{pmatrix} 0 \\ 1 \end{pmatrix} = -1 \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

it is clear that this case produces $\lambda = -1$, this simply means the coming vertical light will not pass through the horizontal polariser. Now what if the coming light is following an angle?. Generally, the photon will have an intensity of $cos^2(\theta)$, where θ is the polariser angle that has a probability amplitudes of horizontal and vertical polarisation.

As explained earlier, the probability amplitude (α) represents the x coordinate, as shown in Fig. 1. Generally, it can be written as $(cos(\theta))$, while β represents y coordinate and written as $(sin(\theta))$ if the length of the vector is 1. This means if the photon is prepared with θ direction, the probability this photon is going through horizontal polariser is $|cos(\theta)|^2$ and the probability to go through vertical polariser is $|sin(\theta)|^2$. Accordingly, a photon with θ angle of polarisation has its own orthogonal state, with probability amplitude $\alpha = -sin(\theta)$ and $\beta = cos(\theta)$ as shown in Fig. 1, where the inner product of the orthogonal states is 0, as shown below where the product of 45 and -45 degree photon states produces 0, which applies to the entangled photons.

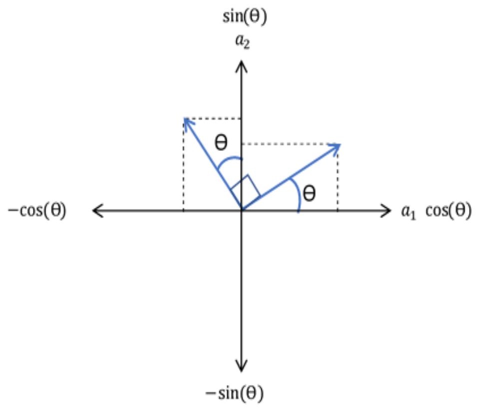

Fig. 1: Representation of orthogonality of a two photons.

$$\langle / | \backslash \rangle = \begin{pmatrix} cos(\theta) sin(\theta) \end{pmatrix} \begin{pmatrix} -sin(\theta) \\ cos(\theta) \end{pmatrix} = 0$$

To generalise this, if a photon is polarised with α angle is going through β polariser. The quantum state probability amplitude is given as

$$|\alpha\rangle = \begin{bmatrix} cos(\alpha) \\ sin(\alpha) \end{bmatrix}$$

and

$$|\beta\rangle = \begin{bmatrix} cos(\beta) \\ sin(\beta) \end{bmatrix}$$

Then, the probability of a photon prepared in α angle state to go through β angle polariser is given as:

$$|\langle\beta|\alpha\rangle|^2 = \left(\begin{pmatrix} cos(\beta) sin(\beta) \end{pmatrix} \begin{pmatrix} cos(\alpha) \\ sin(\alpha) \end{pmatrix} \right)^2$$

$$|\langle\beta|\alpha\rangle|^2 = (cos(\alpha - \beta))^2 \qquad (2)$$

If $\theta = \alpha - \beta$, then this probability returns $cos^2(\theta)$, as explained earlier.

A. Quantum Entanglement

A unique behaviour in quantum mechanics called quantum entanglement, it allows to transfer the quantum state of the photon immediately between two cites that are widely separated [15]. Entangled photons can be generated using spontaneous down conversion process, when a high frequency, strong beam of laser light interacts with a crystal to generate spatially entangled photons. Such theory was investigated in 1935 by Albert Einstein, Boris Podolsky, and Nathan Rosen, acronymed as (EPR), and thereafter by Erwin Schrödinger and described as EPR paradox. They considered this behaviour is impossible as the reality view is violated. Subsequently, this action was described as (spooky action at a distance) by Albert Einstein because the influence between the entangled photons travels at zero time (more than speed of light) through mysterious wave function. Nevertheless, entanglement phenomena was verified experimentally to produce such correlation in many researches such as [16], [17].

It is now possible that one classical bit can drive the laser to generate two or more entangled photons. Meaning, entanglement allows a sender to transmit two or more bits of information using only one classical bit, classically, this is not possible. Once the photons are generated and transmitted, the state of each one is not known as each one of the photons has possibility to hold, for example, a horizontal and vertical polarisation at the same time, as explained earlier. After, the receiver uses a unitary operator, i.e. polariser to force collapsing the received photon to one of its states, i.e. horizontal or vertical polarisation. The special characteristic about entanglement is once one of the photons is measured using a particular polariser, the second photon collapses to opposite polarisation state immediately, which allows us to know the information of other state on the other side. To sum up, there are two incredible entanglement properties that can be utilised in classical communications, first, more than one photons/bits can be generated from one classical bit, second, these generated photons are correlated, which means any operation performed to the first photon, the other photon responds immediately. Mathematically, the two entangled photons system σ can be given as: $|\sigma\rangle = \rho_{00}|0\rangle|0\rangle + \rho_{01}|0\rangle|1\rangle + \rho_{10}|1\rangle|0\rangle + \rho_{11}|1\rangle|1\rangle$, where ρ_{00}, ρ_{01}, ρ_{10}, ρ_{11} are complex numbers representing the probability amplitudes, with their total probabilities $|\rho_{00}|^2 + |\rho_{01}|^2 + |\rho_{10}|^2 + |\rho_{11}|^2 = 1$, where $\rho_{00}, \rho_{01}, \rho_{10}, \rho_{11} = \frac{1}{\sqrt{2}}$, denote the probability amplitudes that the two entangled photons are holding horizontal-horizontal, horizontal-vertical, vertical horizontal, and vertical-vertical polarisation states, respectively [18]. If an entangled system with more than two photons, the number of possible states combinations becomes 2^n, where n denotes the number of entangled photons. It is worth mentioning that it is experimentally possible to produce up to 10 entangled photons successfully [19].

III. QUANTUM CLOUD NETWORKS

Mobile cloud networks, also called cloud radio access networks (C-RAN), are proposed to seize the dramatic increase in the traffic demands, as well as providing improved quality of service [20]. The problem with cloud radio access network is that UE is required to connect to the cloud pool so as its data is processed and sent back to the target UE. Hence, a possible network delay can happen due to enlarged distances that increases the multipath delays/fading, not to mention the delay of packets processing. Another constraint is the burden on the fronthaul links regarding providing the required bandwidth for the increased number of UEs. Part of this communications is dedicated to the control plane signalling. In case of handover, there will be multiple ping-pong communications amongst UE, source BBU, target BBU, and other network units such as mobility management entity (MME) and serving gateway (SGW) to update the moving UE. This issue increases the cost of time delay and power consumption due to transmitting control signals and complexity. Hence, the multiple entangles photons can be utilised to serve as main transport signals amongst the connected RRHs without the need of high level communications amongst the BBUs. The BBU pool is sending the processed data to the RRHs, then the RRHs are sending this to the UEs. If the entangled photons are generated at the pool by triggering the a laser source, a group of entangled photons can be sent to the connected RRHs. It is required to detect these photons at the RRHs side and extract the original data, as shown in Fig. 2. Consequently, the channels between the pool and the RRHs are assumed to be optical fibre channels to ensure the required security. Once the photon is sent to its destinations and one photon is detected at one of the RRHs, it is easily now to determine the state of all other photons received by other RRHs at the same time. This situation cancels the need for noise cancellation procedure at the RRHs. Furthermore, no intra or inter tier communications are required because the BBU pool requires to know the detection state of one RRH only so as the others can be known. Nonetheless, in this work, the consideration of such hidden channel between the entangled photons is ignored as we are interested in the detection of multiple photons and obtaining more than one classical bits from a single bit. Hence, the procedure is to encode a classical bit into a multi-dimensional entangled photons that eventually can be detected at the receiver side as classical bits.

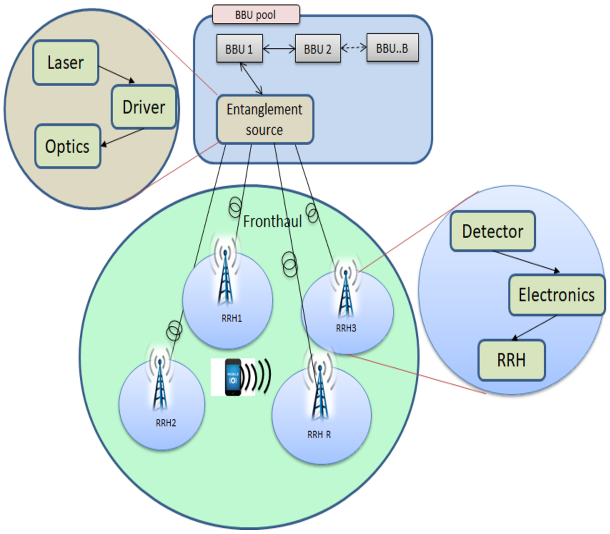

Fig. 2: Cloud networks oriented quantum entanglement.

IV. RELATED WORK

In [21], the cost of classical-quantum adaptation is described. The work in [22] have studied the quantum computing systems from technical point of view, including quantum gates, memory, CPU, error corrections and controlling. In [23], some properties, especially the correlation between classical and quantum quantum system has been studied. In addition, the capacity of some quantum channels is studied in [24]. More extensively, the channel capacities of quantum systems are studied in [25]. Moreover, quantum repeater was proposed in [26] to reduce the error probability that increases exponentially with respect to the length of quantum channel. In [27], a satellite is used to transfer entangled photons or single photon to provide long distance (100 km) solution for quantum networks using optical fiber or wireless links. This work advocates the validity of long distance, entanglement based classical networks. In addition, [28] proposed a model that provides an applicable solution using entanglement distribution method with high fidelity to be utilised in quantum Internet networks. Moreover, based on entanglement availability, the authors in [29] have proposed quantum based Internet scenario that is used when the network UEs have differentiated priority, or the amount of available entanglement pairs is limited. In [30], multilayer optimization technique has been proposed in quantum entanglement based Internet, this method minimizes the execution time of the quantum memory in the node, maximizes the throughput of the entanglement links, and reduces the number those links.

The security while using entanglement is discussed in [31] to permit secure key quBits distribution of instantaneous transmission of information. Another research used a free-space entangled photons distribution over 13 km of noisy atmosphere, was experimental reported in [32]. After such a distance, the experiment showed that entangled pairs can still be survived. The classical information was sent using quantum entanglement assisted channel between two parties, where the quantum, classical and power consumption rates while using coding schemes are all evaluated [33]. This work also proposed a protocol for such type of communications. In [34], entangled photon pairs are used to improve the capacity of the communication system through using the correlation behaviour to encode more number of bits, using optical fiber channel. Finally, the work in [4] have proved that both quantum and classical information are able to communicate without sharing a reference signal by using the correlation of the entangled photon for such purpose.

Finally, Table I below shows the latest technologies, protocols and advances within the field of quantum based communications.

Reference	Technique	Applications
[35], [36]	Optical fibre oriented quantum communications	Ground-ground and ground-space communication protocols
[37]	Non-cloning theorem	Ciphering and security
[38]	Quantum super-dense coding	Encoding/decoding of quantum bits
[39]	Quantum key distribution	Quantum channel security
[40]	Quantum telepathy and error correction	Channel security and error retrieving
[41]	Quantum compression	Noiseless coding
[42]	Quantum concentrating	Teleportation and entanglement transformation
[43]	Entanglement generation	Entanglement distribution and quantum broadcasting
[43],[44], [45]	Quantum channel capacity	Physical properties of quantum communication channels
[46]	Quantum random number generation	Quantum bits coding
[47],[8]	Quantum Networking	-Internet and wireless communications
[48]	Quantum private communication	Land quantum mobile communications

TABLE I: Related Literature

V. PERFORMANCE PARAMETERS

A. *Quantum Based Handover Process*

One of the essential problems in traditional networks is to limit the signalling overhead in the control part. An enlarged number of control plane communications causes more signalling traffic, PC, and complexity [49]. The handover process consumes considerable amount of power and causes latency that participates to call dropping and non-seamless UE's delivery from one RRH to another. Before elaborating on the proposed solution, it is worth explaining the traditional way of transferring the UE's from one RRH to another, as follows: the UE informs its serving/source RRH about the request of handover to the target RRH by examining the peak received power from all possible target RRHs through RRC measurement control signal. Then the source RRH checks the UE's willingness through RRC measurement control signal. Subsequently, the RRH with higher received power is selected as target RRH. After that, multiple connections between the source and target RRHs happen through X2AP application protocol. These connections include resources status request from source to target RRHs, followed by a response from target to source RRH. Subsequently handover request and response between source and target RRHs. After, the status of the UE is transferred to the target RRH along with its UE data that is achieved by the GPRS tunneling protocol (GTP) data plane. Finally, the UE is updated to the new mobility management entity through S1AP protocol. It is worth mentioning the RRHs have no processing capability and the BBUs are all responsible for such procedure. The proposed quantum based method will have some advantages over traditional handover process, as follows:

1) lets assume that RRH1 is served by BBU1, and RRH2 is served by BBU2. Although the UE of RRH 1 is travelled to RRH 2, it still can be served by its serving (BBU1) as there are two (or more) photons (translated to classical bits at the RRH side) are generated from UE's data. Hence, its information are copied instantly to the target RRH2, this situation can save power and time in the pool.
2) This means the travelling UE to the target RRH2 can still be served by BBU1, i.e. the target BBU is not participating in serving the coming UE, and no heavy signalling is needed, with the requirement of UE's status transfer that is necessary for updating at which RRH the UE resides at the moment.
3) Generating several photons that eventually are translated to classical bits means the cloud information are instantly received by entanglement oriented RRHs. This makes updating an establishing new services is much easier and faster than traditional method, where each RRH is allocated different set of information.
4) Interference-free channel through using optical fibres to transfer the photons amongst the cloud center and the RRHs.
5) The studies have showed the X2 interface is facing an enlarged handover failure in the traditional networks, such failure is related to instability and scalability issues. Furthermore, X2 interface needs to be upgraded in all BBUs to the newest release of the standards, this matter is time-consuming and costly [50]. Hence, the entanglement can be a proper solution to overcome the scalability issue.
6) Traditionally, not all the BBUs have direct X2 interface installed amongst them, when no X2 interface is found, S1 interface is the replacement. The two BBUs will be connected to the MME unit to perform handover. In such case, the entanglement procedure represents a perfect replacement of X2 and S1 to achieve the handover.

B. *Quantum Energy Efficiency*

The general formula of the classical entropy is defined as the average amount of information that is received from an information source. In other words, it is the sum of the probabilities of the generated symbols, i.e. $H(x) = \sum_{i=1}^{M} pr_i \log_2 pr_i$, where M denotes the number of symbols, and pr_i is the probability of receiving symbol (i). For example, the entropy of a coin with two symbols, each with 0.5 probability, produces

1bit of information. The quantum analogue of the classical entropy is formulated by Von Neuman Entropy, it can be given as $H(x) = \sum_{i=1}^{I} \lambda_i \log_2 \lambda_i$, where I is the total number of system states, λ_i is the eigenvalue of the state i [51]. Since we are interested in quantifying the energy efficiency of quantum-classical system, we have modified the entropy in terms of received power at the RRH, along with eigen values of the system. We have assumed the power associated with each transmitted photon state is p_i, hence, the entropy is given as $H(x) = \sum_{i=1}^{I} p_i \lambda_i \log_2 p_i \lambda_i$, where $H(x)/sec = W\ log_2(1+SNR)$, is the capacity of the system. Subsequently, the received quantum energy efficiency at the UE end (Q_{ee}) from the cloud center is given by

$$Q_{ee} = \frac{W\ log_2(1+SNR)}{P_{QC}} \tag{3}$$

Where $SNR = \frac{P^t_{n,u} h_{m,u} r_{m,u}}{B\ N_o}$ is the wireless signal to noise (SNR) ratio, W is the system bandwidth. In addition, $P^t_{n,u}$ is the power transmitted from RRH n to UE u, $h_{m,u}$ represents the channel gain from n-th RRH to u-th UE, and N_o is the AWGN received by the UE. In addition, $r_{n,u} = d^{-\alpha}_{n,u}$ denotes the path loss between RRH n and UE u, α is the path loss exponent. Furthermore, $d_{n,u}$ is the straight line distance between n-th RRH and u-th UE, which is given as $d_{n,u} = \sqrt{(x_n - x_u)^2 + (y_n - y_u)^2}$, where x_n, y_n, x_u, y_u indicate the Cartesian x and y axes of the RRHs and UEs, respectively. Moreover, P_{QC} is the PC of the system which is modelled in Section V-C. In addition, the optical power received by the RRH from the cloud center when each photon's state is associated with its own probability $|\langle\beta|\alpha\rangle|^2$, can be given as:

$$P^r_{n,u} = P_{PA} \times \frac{p_{i,n,u}(|\langle\beta|\alpha\rangle|^2)_{i,n,u}}{A_{i,n,u}} \tag{4}$$

where P_{PA} denotes the received signal power amplification at the RRH side. Furthermore, $p_{i,n,u}$, $A_{i,n,u}$ denote the power and attenuation, respectively, of the signal corresponding to state i while travelling to RRH n that is associated to the UE u through the optical fibre channel.

C. Quantum Cloud Power Consumption

It was assume the total PC of the network is denoted as P_{QC}. The PC of the classical side of the cloud network is P_{cloud}, while the PC of quantum entanglement side is $P_{enanglement}$, where:

$$P_{QC} = P_{cloud} + P_{enanglement} \tag{5}$$

The cloud side itself contains many base band units servers that are responsible for processing the base band packets of the UEs. Each server's PC is denoted as P_{server}, where $P_{cloud} = S \times P_{server}$, as S indicates the number of BBU servers. On the other hand, the quantum part of the cloud ($P_{enanglement}$) is consisted of laser's PC (P_{laser}) and detector's PC ($P_{detector}$). Hence, the entanglement PC is given as $P_{enanglement} = L \times P_{laser} + D \times P_{detector}$, where L and D denote the number of Lasers and detectors, respectively. It is worth mentioning that other optical units within the paradigm of entanglement generation are not power consuming, such as BBO crystal, beam splitter, attenuation units, etc. P_{QC} is also subjected to the effects of other losses found within the server construction, such as, AC-DC, DC-DC and cooling loss. These losses are linearly scaled with other units' PC and approximated by using loss factors (σ_{DC}, σ_{AC}, σ_{cool}) to represent AC-DC, DC-DC and cooling, respectively [52]. Successively, the total PC of quantum cloud (P_{QC}) is updated as the combination of cloud PC and its losses PC:

$$P_{QC} = \frac{P_{cloud} + P_{enanglement}}{(1-\sigma_{DC})(1-\sigma_{MS})(1-\sigma_{cool})} \tag{6}$$

The other part of the modelling is related to the RRH's PC (P_{RRH}). The RRH is also constructed of many units, it is modelled as:

$$P_{RRH} = \frac{P_{PA} + P_{RF} + P_{detector}}{(1-\sigma_{DC,R})(1-\sigma_{MS,R})} \tag{7}$$

Where $P_{PA} = P^t_{n,u}/\eta_{PA}$ is the PC of the power amplifier and η_{PA} is its efficiency. In addition, $\sigma_{DC,R}$ and $\sigma_{MS,R}$ represent RRH's DC and RRH's MS loss factors, respectively, finally, P_{RF} is RF unit's PC. Subsequently, the total network PC is given as the combination of quantum-classical and RRH part, as follows:

$$P_Q = P_{QC} + P_{RRH} \tag{8}$$

D. Delay Analysis

In cloud networks, the total time delay of handover will be little less traditional networks as the BBUs are located in one place [53]. Although orders of ms time delay seems insignificant. However, in a view of mobile communications, such delay is considered large and it is inherently originated due to the protocol stack multiple communications and processing. This is because the processing delay is much higher than link delay no matter how far the BBUs are placed. To model the delay, we have assumed the link delay from RRH to the pool is $\tau_{n,o} = d_{n,o}/c$, where (o) denotes the pool's geographical position that is assumed to be at the origin of area of interest where the cloud centre resides, where $d_{n,o} = \sqrt{(x_n - x_o)^2 + (y_n - y_o)^2}$, where x_n, y_n, x_o, y_o indicate the Cartesian x and y axes of the RRHs and cloud centre, respectively. c is the speed of light. In case of optical fiber links, $\tau_{n,o} = d_{n,o}/c_{opt}$, where ($c_{opt} = c/ind$) is the speed of light inside the optical fiber, and (ind) is its refractive index. Subsequently, the delay from the UE to the RRH is denoted as $\tau_{n,u} = d_{n,u}/c$, this link is only wireless.

The work in [54] has mentioned that the execution/processing time is linearly proportional to the processed RBs and modulation coding scheme (MCS) that is used to transmit these RBs. Therefore, a model is required to combine such concepts. If we assume (τ_{BBU}) is the execution time of the BBU processing, where $\tau_{BBU} = \tau^{int} + (mod * RB)$, where τ^{int} represents the initial device delay due to other functions rather than MCS, the latter is denoted by the constant factor (mod) which indicates the degree of increment. Hence, the total delay of traditional network can be expressed as $\tau_{traditional} = \tau_{n,o} + \tau_{n,u} + \tau_{BBU}$ where the handover via X2 interface is assumed to be embedded within the total BBU server processind delay, i.e. τ_{BBU}.

If entanglement case is discussed, source/laser and detector are also found within the BBU pool and RRHs. Hence, their delays are added to the total formulation of entanglement case, as follow: $\tau_Q = \tau_{n,o} + \tau_{n,u} + \tau_{laser} + \tau_{detector} + \tau_{BBU} - \tau_\triangle$, where τ_Q represents the total delay of quantum scenario. In addition, τ_{laser}, $\tau_{detector}$ are the time delays of the laser source and detector, respectively. $\tau_\triangle$ denotes the delay gain when deducting the delay of handover process, that is assumed as 10% of the BBU server delay, i.e. $\tau_\triangle = \tau_{BBU} - \tau_{BBU} \times 0.9$. This gain is from one BBU processing, this gain can be further extended to as many as the number of entangled photons as each entangled photon represents an elimination for X2 interface in the tagged BBU. For example, when we have 4 entangled photons, this means the delays of 4 BBUs are mitigated, and so on. Subsequently, the delay gain will be equivalent to $(|\sigma\rangle \times \uplus)(\tau_\triangle - \tau_{laser} - \tau_{detector})$, where $\uplus$ denotes the number of entangled photon pairs.

E. Power Gain Analysis

The more entangled photons are used, the more saving in the power can happen. The UE that is travelled from one cell to another can still be served permanently from its original BBU until it reaches the maximum number of served UEs. In this case, the UE will be handed to the target cell in a relaxed period of time. If the same UE is also moved to another cell, the same procedure is still valid, this situation can happen as long as the BBUs reside within the same BBU pool. Once the UE moved to another BBU pool, inter-BBU pool handover is required.

However, this work only discusses the case of single BBU pool with group of BBUs. Generally, the PC of the network is divided to two parts, static and dynamic. The static part is the amount of power consumed when there is no transmitted power or processed resource blocks. This type of PC is unavoidable and non reduce-able since it is only responsible for operating the device/server itself. On the other side, the dynamic PC totally depends on the transmitted power to the UEs or the processed load/packets. Therefore, once the transmitted power is reduced or the number of served UEs are reduced, this dynamic type of consumption will be alleviated. The transmitted power from the BBU pool can be received by a number of RRHs that are equivalent to the number of generated entangled photons. This situation can save power and replaces the case of generating separate data for each RRH. It also reduces the number of entanglement sources, for example 8 entangled photons can serve 8 RRHs at the same time. These 8 RRHs are no longer needed to generate data for the new arrival UE, rather, directing the received UE data from the sending BBU to target RRH, then to the UE. Accordingly, the X2 PC is deducted from the cloud PC when using entanglement case. Hence, we have assumed the amount of power consumed by X2AP protocol is ($P_\triangle$). Subsequently, the total cloud PC is updated:

$$P_{QC} = \frac{(P_{cloud} - P_\triangle) + P_{enanglement}}{(1-\sigma_{DC})(1-\sigma_{MS})(1-\sigma_{cool})} \tag{9}$$

where $(P_\triangle = P_{BBU} - 0.8 \times P_{BBU})$ is the gain in the PC.

VI. SYSTEM COMPLEXITY

There are several limitations regarding adapting quantum methods into the more convenient traditional or cloud networks. Generally, the cost of installing and managing the complexity of entangled photons generation can be higher than the cost of installing ordinary optical fiber based mobile cloud networks, where the photons can be dealt with as classical bits only. Since this work only used the duplicate entangled photons to provide the necessary UE information in time without any cost, there still another characteristic of the entanglement theory is not yet utilised, i.e. the correlation channel amongst the entangled photons. Utilising the quantum hidden channel of entangled photons can offer a solution in case one of the photons is highly attenuated or not detectable. By using feedback signals amongst the tagged RRHs, each one can reveal its detected photon state and what time it is received. When a particular RRH did not detect its photon at the allowed time slot, the other RRHs can share their states to compensate the missing information of the tagged RRH. However, this type of communications require an advanced protocol and dedicated algorithm to manage the feedback signals of the participating RRHs. In addition, implementing the quantum methods requires more caring while setting up the hardware equipment, also it requires more maintenance. It is worth noticing that this research has used Matlab software to simulate the proposed model and produce the results.

VII. RESULTS AND ANALYSIS

The detector unit consumes insignificant amount of power, with only 10V DC and 15mA or less current, and less than 1W of power supply. For fair results, we assumed the power supply is identical to its PC, similarly to the laser PC. Furthermore, we have assumed the response time of the detectors is 10ns and equivalent to its processing delay, while the laser driver circuit's delay is about 1μsec, as shown in Table II. It was mentioned in [2] the LTE control plane can reach up to 100 ms. However, we used worst case scenario, we have assumed the delay due to handover signalling is only 10 μsec. Therefore, the gain in the delay will be $\tau_\triangle - \tau_{laser} + \tau_{detector}$ as described in V-D. Since the amount of $\tau_\triangle$ is higher than the detector and laser delays together (about 1.01 μsec), the gain in the delay will be about 9μsec as long as the link delays $(\tau_{n,o} + \tau_{n,u})$ are identical for both traditional cloud and entanglement based cloud cases. Accordingly, Fig. 3 shows the time delay comparison of C-RAN and quantum based C-RAN for different number of processed resource blocks while the system used 8 entangled photons. Processing more number of resource blocks means the delay becomes larger as the dynamic based time delay is linearly scaled with the number of resources block, as explained in Section V-D.

Note that when the number of entangled photons is increased, the saving in the delay can be increased too. Accordingly, Fig.4 shows the delay saving for different number

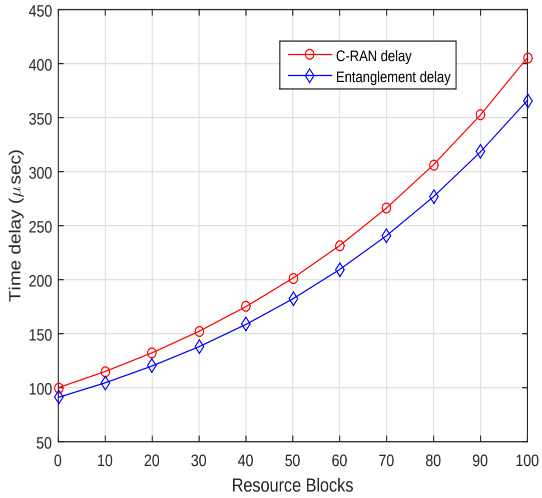

Fig. 3: Time delay comparison between C-RAN and quantum entanglement based C-RAN for different number of resource blocks.

of entangled photons while processing the same amount of resources blocks of Fig. 3. When the number of entangled photons increases, each RRH's delay will be saved, which explains why more saving happens within the quantum case as the number of generated photons is increased.

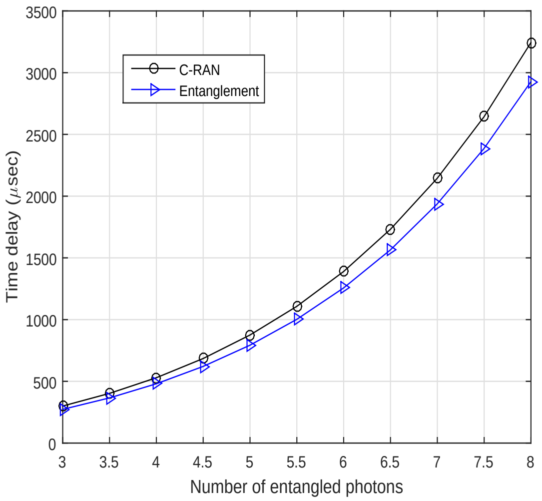

Fig. 4: Time delay comparison between C-RAN and quantum entanglement based C-RAN for different number of entangled photons.

Regarding the PC, the signalling overhead is consuming considerable amount of energy, it can reach about 20%, up to 80% of CPU utilisation [2]. Taking into consideration the amount of power added to C-RAN system by the laser and detectors necessary for entanglement generation, a comparison can be made between both systems. Hence, Fig. 5 shows the PC comparison for different count of BBUs and RRHs, assuming the overhead of signalling is only 20% of the CPU/BBU consumption. It was also assumed that each BBU is connected to one laser and detector, same procedure holds true for the RRHs. It can be shown that a slightly increase in the PC of quantum case compared to traditional C-RAN as the number of installed detectors and lasers is large.

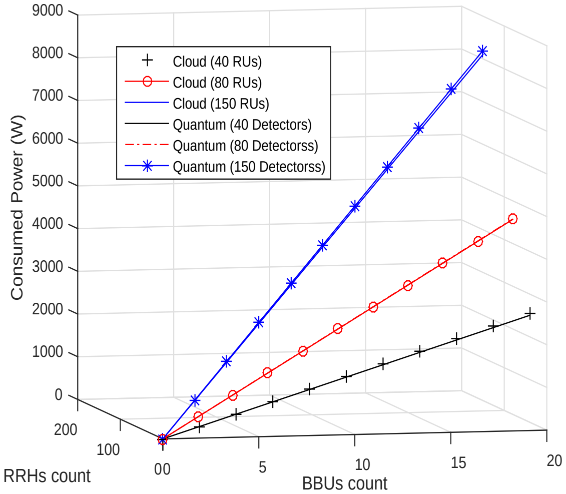

Fig. 5: Power consumption comparison between C-RAN and quantum entanglement based C-RAN for different number of RRHs and BBUs.

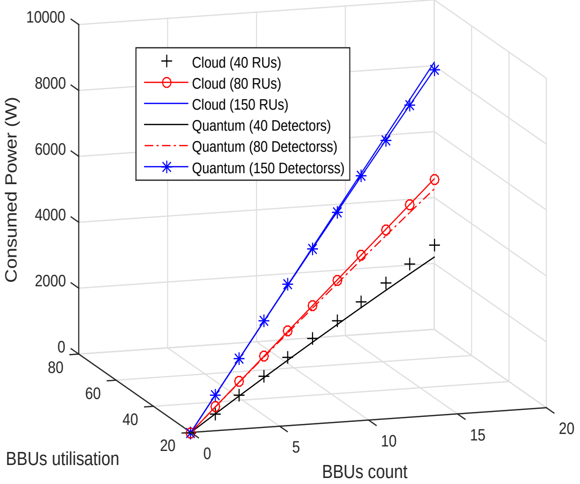

Fig. 6: Power consumption comparison between C-RAN and quantum entanglement based C-RAN for different number of BBUs and its utilisation percentage.

However, such cost can be mitigated in two folds: first, practically, the number of lasers can be reduced as one driving laser can feed as many as the entanglement based RRHs, which saves more power by using one entanglement source for several RRHs. Second, the signalling overhead can be increased to more than 20% as mentioned in [2]. Hence, Fig. 6 shows the PC comparison for different percentage of signalling overhead (BBU utilisation) while holding the same number of RRHs of Fig. 5. It can be shown the PC of quantum case is less than traditional C-RAN.

The PC can affect the energy efficiency of both systems. Once the PC is increased, the energy efficiency is decreased. We have assumed the optical fiber channel has no effect up on the signal level, i.e., $A_{i,n,u} = 1$. In the literature, there are different type of channels. However, any type of channel can be used for both systems will have equalised effect, hence, the channel is assumed ideal. However, this is further compromised by not adding power gain to the received signal by the RRH so as both effects can be equalised, i.e. $AP = 1$. Successively, Fig. 7 shows the energy efficiency comparison of both C-RAN and quantum entanglement based C-RAN, for different number of RRHs and processed resource blocks. It is clear the more processed resource blocks means more power consumed in the BBU, which indicates less received energy efficiency at the UE's level.

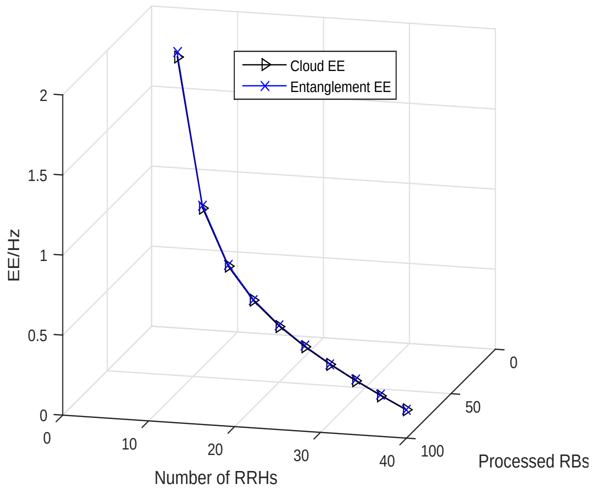

Fig. 7: Energy Efficiency comparison between C-RAN and quantum entanglement based C-RAN for different number of RRHs and processed resource blocks.

Factor	Traditional(Generated)	Unit
σ_{DC}	0.910	-
σ_{MS}	0.9250	-
σ_{cool}	0.90	-
$\sigma_{DC,R}$	0.910	-
$\sigma_{MS,R}$	0.9250	-
ind	1.3	-
mod	0.014	-
α	3	-
$A_{i,n,u}$	1	-
AP	1	-
P_{RF}	12.9	W
P_{PA}	29.6528	W
P_{BBU}	29.4	W
τ^{int}	50	μsec
τ_{laser}	1	μsec
$\tau_{detector}$	1	$nsec$
N_o	$\frac{dB}{Hz}$	-10

TABLE II: Model Parameters

VIII. CONCLUSION AND FUTURE WORK

This work has showed that quantum computing can be utilised as a solution for the classical cloud mobile networks. It proposed an evaluation and futuristic solutions the cloud based cellular communications, particularly for C-RAN. The traditional cloud networks encounter an enlarged delay due to handover process via X2AP protocol. Therefore, this paper showed that quantum entanglement phenomena can be used to decrease such cost through modelling the latency of both paradigms. Without any compromisation of PC, this work showed that a quantum based paradigm can boost the energy efficient of the traditional cloud network, with a possibility of power saving when using more entangled photons. This work also allows inter-BBU pools entanglement based handover when the handover participating BBUs reside on different pools, the source BBU can still serve the travelling UE while the background communications to update the UE's position happen in a relaxed period of time. Another case is that when there are few UEs in the target RRH and some of them are still being served by source BBU, the residual UEs of the target BBU can be handed over to the source BBU by using resources sharing algorithm to switch off the target BBU and save power, which further improves the energy efficiency of the system.

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