Application of Quantum Computing to Accurate Positioning in 6G Indoor Scenarios

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***Abstract*—6G will lay its foundations on new paradigms and requirements. This new technology is expected to provide global coverage, exploring a huge spectral chunk (sub-6 GHz, mmWave, THz and optical frequency bands) to further increase data rates and connection density. In addition, 6G networks will enable a new range of smart applications with the aid of Artificial Intelligence, Big Data technologies and the emerging paradigms of Quantum Computing and Quantum Machine Learning. This paper focuses on these new paradigms and proposes an indoor location method based on the well known Euclidean Distance in its quantum version. Specifically, an example of this use case is shown, which is executed in one quantum computer from IBM Quantum Experience.The paper analyses the obtained results while exploring new challenges and fields of application of the technology. Results show that the quantum approach is accurate enough to calculate Euclidean Distance between two vectors while outperforming classical computation if vector size is big enough.**

***Index Terms*—Quantum Computing, 6G Wireless Communications Networks, Indoor Localization**

I. Introduction

Researchers are starting to focus on the sixth generation (6G) wireless communication networks. 6G will have requirements of high time and phase synchronization accuracy and will have to provide near full geographical coverage, sub-centimetre geolocation accuracy and millisecond geo-location update rate to meet use cases [1], [2]. Three interesting categories for the upcoming technology, Intelligent Life, Intelligent Production and Intelligent Society, have been proposed in [3]. Health monitoring and primary diseases prevention, "informatization and networkization" in agriculture and industry, super transportation, universal public services and refined social governance fall into the mentioned categories as examples of applications. 6G expects to have many sensors, featuring at the same time massive MIMO deployment schemes, which will eventually evolve into radio stripes, deploying one antenna every few centimetres. This entails the management of huge data amounts for the provisioning of location services based on the footprint of the radio signal into the devices. Thousands of transmitters towards thousands of receivers creating fingerprint vectors of millions of elements.

Faced with such big datasets generated by using extremely heterogeneous networks, diverse communication scenarios, large numbers of antennas, wide bandwidths, and new service requirements, 6G networks would likely require the use of Quantum Computation (QC) due to the fact that classic computers will not be able to treat that amount of data fast enough, and it will be necessary to implement different solutions based on quantum schemes.

Indoor localization is the task of obtaining a device or user location in an indoor environment. It has wide-scale applications in many sectors of everyday life such as health, industry, building management and novel systems, for example, Internet of Things (IoT), smart cities, smart building, Machine Type Communication (MTC) and so on [4], [5].

The next generation must include high accuracy systems to enable features such as pencil beamforming on mmWaves or self-driving robots inside a factory, for example. Those applications require knowing the position of the device with millimetric accuracy, not provided by the actual systems.

This article presents a brief overview of Quantum Computing and its main characteristics. An efficient solution for an indoor location use case based on the Quantum Euclidean Distance using Qiskit is proposed and run on an IBM Quantum Experience system. The rest of the paper is organized as follows: Section II shows the main QC characteristics, Section III provides the details of our indoor localization proposal and an example of the use case based on the Quantum Euclidean Distance. Finally, Section IV draws the main conclusions of the paper.

II. Quantum Computing

The idea behind what a quantum computer is has different perspectives. From Moore's Law perspective, when the size of transistors is less than 7 nm reaching sub-atomic scale, digital electronics that is based on classical physics fails. At this scale, quantum physics dictates the behaviour of matters and any system that is built using quantum physics is called Quantum Computer. From a physics perspective, a binary digit can be represented as a photon with vertical polarization as 0 and horizontal polarization as 1. These polarizations could change, for example, to the angle of 45 degrees with proper manipulation and usually occurs at the sub-atomic level in particles, called Coherent Superposition. This phenomena is explained by quantum physics, and it can be used to create Information Systems that are called Quantum Computers [6].

Just as the bit is the fundamental concept of classical computation and classical information, quantum computation and quantum information are built upon an analogous concept, the quantum bit (qubit). Furthermore, just as a classical bit has a state, either 0 or 1, a qubit also has a state. The two possible states for a qubit are the states $|0\rangle$ and $|1\rangle$. " $|\rangle$" is called the Dirac notation, the standard notation for states in quantum mechanics [7].

A. Quantum features

Quantum physics has specific features that do not appear in classic systems. These principles, if leveraged properly, can create new procedures, applications, and enable new paradigms of quantum information technology. The main of those are superposition, entanglement and quantum parallelism.

Superposition is a principle inherent to quantum mechanics, describing quantum states. Classically, bits could take a value of 0 or 1, depending on if the transistors were "low" or "high". In quantum computing, states are non-deterministic and could be in a superposition of basic states, where qubits can take a state other than $|0\rangle$ or $|1\rangle$ forming a linear combination of states:

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle, \tag{1}$$

where α and β are complex numbers. The measurement of a qubit in superposition state involves that it will collapse to one of its basis states ($|0\rangle$ or $|1\rangle$). The probability of having $|0\rangle$ or $|1\rangle$ as the result of the measure is known, being $|\alpha|^2$ and $|\beta|^2$, respectively.

On the other hand, entanglement is a strange but useful phenomenon where quantum states are maximally entangled. This means that two or more qubits are linked and dependent on each other, no matter where they physically are. Being in the same state, they can be evaluated in a single step, which means that if one of the entangled qubits is measured, the states of the rest of the qubits are also known [8].

Finally, quantum parallelism is a fundamental feature in many algorithms, which allows quantum computers to evaluate a function $f(x)$ for many different values of x simultaneously. This is possible due to the superposition property of quantum mechanics [9]. If the reader is interested in more details on quantum computation, a good introduction, specifically in Qiskit, is found at [10].

III. Indoor Localization with Quantum Computation

Indoor localization has always been a challenge for mobile communications. Classical solutions using the fingerprint method are described, as example, in [11], where bluetooth low energy beacons are used to estimate the accurate location of devices with good results. However, higher precision and faster localization can be achieved in next generations making use of quantum computers. In this field, [12] proposes a quantum fingerprint matching algorithm using WiFi hotspots to determine the localization based on the Received Signal Stregth Indicator (RSSI). Results show the potential of quantum computers, which could currently provide higher accuracy using the system proposed in this paper.

Values coming from each sensor or antenna as RSSI, Time of Arrival (ToA), Angle of Arrival (AoA), or Time Difference of Arrival (TDoA) can estimate the user's location as described in [13]. The more antennas, the more accurate the system will be, but computational time will rapidly increase with vector size.

The method proposed in this paper first needs a measurement campaign creating a grid on the location area with measures of different parameters on each tile coming from all the access points with coverage in the area. The more access points, the bigger size of the vector, that could be in the order of tenths of thousands in a massive MIMO deployment case. A big database including RSSI, ToA, AoA or any parameter considered will be created as an offline step. That database will be used to compare the real-time (online) received values with the stored ones. Small tiles mean higher accuracy but will take longer to compute for a classic computer due to the size of the data base. Quantum computers can help reduce the complexity of this problem using the properties of superposition in order to perform simultaneous calculus of the euclidean distance between the real time values and the stored database.

An iterative solution, complementary with the previous concept and shown in Figure 1, is proposed in this paper to reduce the number of tiles checked during the process. First, bigger tiles are compared to reduce the search space. The space is divided into, for example, four tiles in which the device could be located. Once it is determined that the device is in a certain tile, marked with red in the Figure 1, that one is divided into another four smaller tiles, and the device will be located in a smaller tile. This process is repeated until the smallest tile with stored values is covered, reaching high accuracy with relatively a low number of vector comparisons. Each comparison of data size between stored and real time will be done simultaneously, meaning a lot of radio parameters could be stored and evaluated in order to boost the accuracy in case high precision is needed.

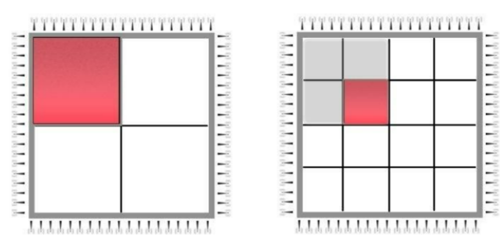

Fig. 1. First two iterations of the indoor localization proposal.

A. Quantum euclidean distance

The calculation of distances is one of the most important operations which is performed in many fields. Measuring similarity between objects can be done differently and the Euclidean Distance, the shortest distance between two points, is very well known. A method for estimating localization based on the Quantum Euclidean Distance is presented below.

The first step is to encode the classical data into quantum states, what is known as quantum embedding. It takes a classical data point X and translates it into a set of gate parameters in a quantum circuit. There are some techniques to do it, such as basis embedding, angle embedding, amplitude embedding and so on. The last one mentioned was used in this paper. It normalizes the data dividing the original vector by its norm. The main advantage of this method is that it just needs a few qubits for its implementation.

Once the classical data is encoded, the next step is to figure out how to know "the distance between two quantum states" (how similar they are). The metric of similarity can be defined based on two extremes: the quantum states are the same state, or they are perfectly orthogonal. The swap test operator (Figure 2) expresses the overlap (inner product) of the two quantum states ($|\psi\rangle$, $|\phi\rangle$) in terms of measurement probability of an auxiliary qubit, called ancilla, being in state $|0\rangle$. If the probability $P(|0\rangle) = 0.5$ means that the states are orthogonal, whereas the probability $P(|0\rangle) = 1$ indicates that the states are identical. The H gate is applied to the ancilla qubit ($|0\rangle$) to obtain a superposition (state 0 and 1 with equal probabilities).

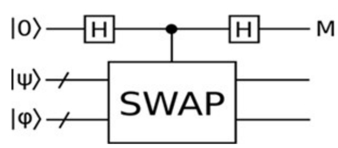

Fig. 2. Swap test operator.

There are two vectors, one with the real time parameters and the other one with the stored ones. With the swap test as a tool, euclidean distance in its quantum version can be calculated.

Vector R contains the real time parameter measured and vector A the stored values of the same parameter, which can be, as mentioned, RSSI ToA, AoA, among others. Euclidean distances must be calculated using a single parameter but a weighing of various distance calculus of different variables can be performed in order to achieve more accurate results.These values must be encoded into quantum states $|R\rangle$ and $|A\rangle$.

Then, to produce the states ($|\psi\rangle$, $|\phi\rangle$), the tensor product is to be used as follows:

$$|\psi\rangle = \frac{1}{\sqrt{2}}[|0\rangle \otimes |R\rangle + |1\rangle \otimes |A\rangle], \quad (2)$$

$$|\phi\rangle = \frac{1}{\sqrt{Z}}[|R||0\rangle| + |A||1\rangle]. \quad (3)$$

The next step is to calculate Z as

$$Z = |R|^2 + |A|^2. \quad (4)$$

The quantum euclidean distance is obtained solving

$$D^2 = 2Z|\langle\phi|\psi\rangle|^2. \quad (5)$$

Something interesting about the states above $|\psi\rangle$ and $|\phi\rangle$ is that they are not of the same dimension. $|\phi\rangle$ will be always a single qubit state. So, the preparation of two states, in this case, will require $O(log(N)) + 1$ qubits, where N is the dimension of the initial vectors. Figure 3 shows a simple circuit example that calculates the euclidean distance in its quantum version.

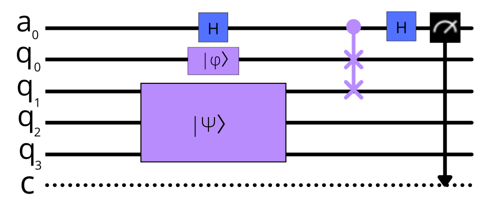

Fig. 3. Quantum circuit example.

B. Quantum indoor localization

This subsection aims to illustrate an example of the described system, which was executed on ibmq_casablanca, one of the IBMQ devices [14]. In order to test the performance, RSSI will be evaluated for 8 antennas on 2 iterations (Figures 4 and 5). Number of antennas and iterations can increase if the size of the quantum computer allows it, however this example's goal is to show the performance in a basic scenario in order to visualize it better. The indoor scenario is a square office. Eight antennas are distributed around it, each antenna experiencing a RSSI level on the device to be located. Next, the two iterations and the results given by the quantum computer will be explained.

1) Iteration 1: The vector [R] contains the RSSI values of each antenna from 1 to 8. The points [A], [B], [C] and [D] are in the center of each sub-square and have pre-stored the RSSI received in that position for all the analyzed antennas. Figure 4 illustrates the real position of the device and the antennas used to accurately determine it. With enough qubits, the system could use all the antennas or radio stripes available in order to gain accuracy while calculate the distance, since more antennas in the system do not increase computational time. Table I shows the pre-stored RSSI received values for each square center and at the live position [R]. [RX] is defined as the euclidean distance from the stored RSSI values in [X] (varying for each center square) to the real position of the device [R].

TABLE I
VALUES FOR ITERATION 1

Antenna measured	**RSSI (dBm)**				
	R	***A***	***B***	***C***	***D***
1	-85	-82	-95	-93	-106
2	-82	-77	-90	-90	-104
3	-98	-99	-80	-107	-96
4	-91	-85	-74	-100	-78
5	-93	-95	-109	-82	-94
6	-78	-87	-99	-74	-75
7	-103	-107	-98	-96	-81
8	-74	-78	-81	-78	-88

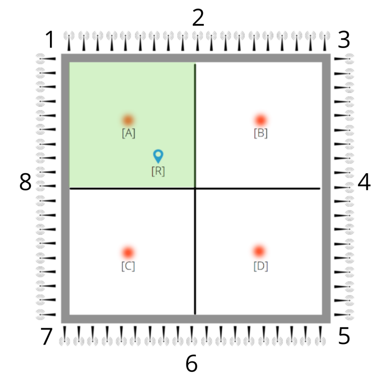

Fig. 4. First iteration square divisions.

The euclidean distance results given from the quantum computer and from a classic computer are summarized in Table II, where [A] is the closest point to the device [R]. This means that the second iteration will subdivide [A] square into 4: [AA], [AB], [AC] and [AD] and repeat the process to enhance the accuracy. Note that these values are not the real distance values since quantum computers still have errors in qubit calibration, but the accuracy is good enough to determine the square where the device [R] is located.

TABLE II
DISTANCES IN DECIBELS OBTAINED FROM ITERATION 1

Parameter measured	Vector				
	RA	***RB***	***RC***	***RD***	***Smallest***
Classic. Eucl. Dist.	13.71	39.34	22.18	42.28	RA
Quantum. Eucl. Dist.	13.91	39.42	23.35	42.19	RA

2) Iteration 2: Square [A] is now divided into [AA], [AB], [AC] and [AD], the points in the center of each sub-square are marked and also have pre-stored the RSSI received in that position for all the analyzed antennas. Figure 5 shows the real position of the device in this new division. Table III contains the RSSI values received and stored for each center square and the position of [R].

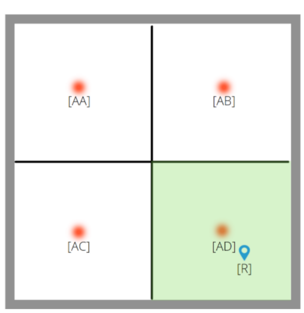

Fig. 5. Second iteration square divisions.

The euclidean distance results given from the quantum computer are summarized in Table IV, where [AD] is the closest point to the device, located in [R]. This means that the third iteration should subdivide [AD] square into 4: [ADA], [ADB], [ADC] and [ADD] and repeat the process until the desired accuracy is reached.

TABLE III
VALUES FOR ITERATION 2

Antenna measured	RSSI (dBm)				
	R	***A***	***B***	***C***	***D***
1	-85	-78	-82	-80	-87
2	-82	-89	-74	-76	-86
3	-98	-101	-90	-102	-95
4	-91	-94	-95	-93	-87
5	-93	-99	-98	-99	-90
6	-78	-85	-87	-84	-77
7	-103	-106	-108	-91	-95
8	-74	-76	-79	-80	-74

TABLE IV
DISTANCES IN DECIBELS OBTAINED FROM ITERATION 2

Parameter measured	Vector				
	RAA	***RAB***	***RAC***	***RAD***	***Smallest***
Classic. Eucl. Dist.	14.63	17.56	18.25	10.91	RAD
Quantum. Eucl. Dist.	14.91	17.70	18.29	11.08	RAD

As a result, after two iterations, the system can determine that the device is near [AD]. Equation (6) gives the maximum error of the localization procedure, in meters, depending on the number of iterations n and the side of the original square L.

$$MaxE = \sqrt{\left(\frac{L}{2^{(n+1)}}\right)^2 + \left(\frac{L}{2^{(n+1)}}\right)^2} \tag{6}$$

C. Quantum errors and supremacy expectations

Quantum computers are still far from being totally stable and errors occur due to the lack of perfect control of the atom. This is the reason why a number of iterations were run in a real quantum computer with different number of shots to check how many were necessary to achieve a valid result. Figure 6 shows the relative error of the quantum computer while calculating the quantum euclidean distance depending on the number of shots. A relative error of 100% means that the distance calculated by the computer is twice the real one. A higher number of shots provides better accuracy but requires longer execution time. Figure 6 also shows that 4000 shots seems to be enough in this case, for the specific quantum computer used, taking about 7 seconds to calculate the distance. Ideally, with better stability of the quantum computer, less iterations would be required tending to decrease this time by three orders of magnitude, ideally.

A comparison of the time required to compute the euclidean distance between a classic and a quantum computer (ibmq_casablanca) is depicted in Figure 7. It also shows when a quantum computer would outperform a classic one, in other words, when will quantum supremacy be reached for this practical case. Two aspects require clarification. On the one hand, quantum computers are reducing execution time lighting speed. Systems available two years ago took twice the time to perform the same operation as compared with the one performed on ibmq_casablanca at the moment of writing this paper. This evolution would make this application feasible in less than 5 years according to predictions that point that this calculus will take less than one second in that moment. In addition, with the rise of better-calibrated systems, less than 4000 shots would be required in the future, which will also reduce quantum computation time. On the other hand, to increase the accuracy of fingerprint-based location algorithms the size of the information collected is to be increased. Classic computers do not scale well with this size, while quantum computers will require the same time to perform any size operation and, therefore, will reach supremacy when the length of the information vector is big enough. This can be easily reached, as explained, with massive radio stripes, sensors and the upcoming 6G applications with tons of information to be collected and treated to enable millimeter accuracy.

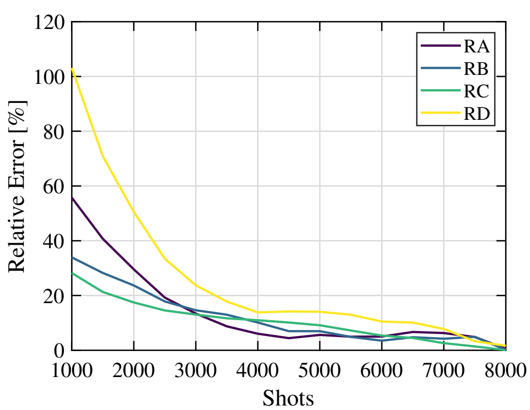

Fig. 6. Relative error in the first iteration.

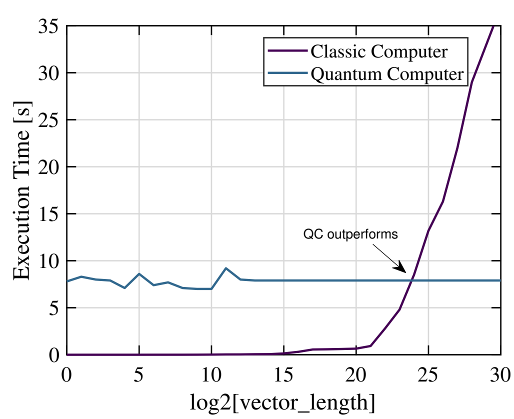

Fig. 7. Time taken to calculate distances.

IV. Conclusions

This paper has applied quantum computation to real positioning as potential enabler for millimeter-range indoor localization. Results show that quantum supremacy for the euclidian distance calculation is reachable with relatively big size vectors, which could be the case in a 6G context in which the number of devices and access points will be massive. Other examples of feasible applications fields for quantum computation are face recognition, since database increases with the number of users to be recognised, or efficient routing through IoT nodes, an optimization problem that also scales incredibly fast with the number of nodes.

Due to the nature of quantum computers, many shots still need to be executed in order to obtain an accurate result for the operation. In the last five years, quantum computers have largely increased both their number of qubits and their quantum volume or accuracy. The road-map of leading company IBM foresee systems of 1121 qubits in 2023, which could easy cover applications as the one purposed in this paper. In addition, quantum volume is also improving fast in a worldwide contest for the leadership in the matter. Good quality well calibrated qubits is the real key to overcome the probabilistic nature of quantum physics and reach quantum supremacy.

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