Towards Quantum Computing for Location Tracking and Spatial Systems

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ABSTRACT
Quantum computing provides a new way for approaching problem solving, enabling efficient solutions for problems that are hard on classical computers. With researchers around the world showing quantum supremacy and the availability of cloud-based quantum computers, quantum computing is becoming a reality. In this paper, we explore the different directions of the use of quantum computing for location tracking and spatial systems. Specifically, we show an example for the expected gain of using quantum computing for localization by providing an efficient quantum algorithm for RF fingerprinting localization. The proposed quantum algorithm has a complexity that is exponentially better than its classical algorithm version, both in space and running time. We further discuss both software and hardware research challenges and opportunities that researchers can build on to explore this exciting new domain.

CCS CONCEPTS
• Hardware → Quantum technologies; • Human-centered computing → Ubiquitous and mobile computing;

KEYWORDS
quantum computing, localization, next generation location tracking, quantum spatial algorithms and systems

1 INTRODUCTION
Quantum Computing (QC) is a new field at the intersection of physics, mathematics, and computer science. It leverages the phenomena of quantum mechanics to improve the efficiency of computation. In particular, to store and manipulate information, quantum computers use quantum bits (qubits). Qubits are represented by subatomic particles properties like the spin of electrons or polarization of photons. Quantum computers leverage the quantum mechanical phenomena of superposition, entanglement, and interference to create states that scale exponentially with the number of qubits, potentially allowing solving problems that are traditionally hard to solve on classical computers [19].

In 1994, Peter Shor presented a theoretical quantum algorithm that could efficiently break the widely used RSA encryption algorithm [29]. In 1996, Lov Grover developed a quantum algorithm that dramatically sped up the solution to unstructured data searches from $O(n)$ to $O(\sqrt{n})$ [12]. Since then, interest in QC has sparked with a number of big companies and startups investing in realizing quantum computers and providing tools for programmers to develop quantum algorithms. This materialized in currently having real cloud-based quantum computers with free accounts to researchers [10, 15] as well as a large number of quantum programming languages and simulators [8, 11, 15].

In this paper, we explore the different directions of the use of quantum computing for localization and spatial systems. Specifically, we give an example of a quantum RF fingerprint-based location tracking algorithm that requires space and runs in $O(M \log(N))$ as compared to the classical algorithms that require space and runs in $O(MN)$, where $N$ is the number of access points (APs) in the environment and $M$ is the number of fingerprinting locations.

We end the paper by a discussion of the different opportunities offered and challenges posed by quantum computing to the fields of location tracking and spatial systems.

2 BACKGROUND
In this section, we describe the basic concepts and notations of quantum computing.
The measurement process is not reversible as the state of qubits at the same time.

2 register is able to store all the classical register of size \( n \), which lives in a 2\(^n\) dimensions. A quantum register is able to store a single value of the \( 2^n \) possibilities spanned by \( n \) classical bits, a quantum register is able to store all \( 2^n \) possibilities spanned by the qubits at the same time.

Finally, the qubit state collapses to the observed classical bit value. The collapsed state represents only one of the possible states that the qubits were in before measurement, but the superposition of states can be used to increase the probability of obtaining the correct answer. This is known as quantum parallelism.

A quantum bit (qubit) is the fundamental building block of quantum computers. It is the quantum version of the traditional classical bit. However, unlike the classical bit, which can be either zero or one; qubits can be in a superposition state of both zero and one simultaneously. The superposition enables a quantum computer with \( n \) qubits to process \( 2^n \) possible states at the same time. This is commonly referred to as quantum parallelism.

A common way to mathematically formalize quantum computing concepts is by using the Dirac notation [19]. A qubit is represented by a linear superposition of basis vectors \( |0\rangle, |1\rangle \) as \( |\psi\rangle = \alpha |0\rangle + \beta |1\rangle \), where \( \alpha \) and \( \beta \) can in general both be complex numbers called probability amplitudes. The state of qubit satisfies the normalization condition \( |\alpha|^2 + |\beta|^2 = 1 \). When a qubit is measured, its state collapses to either \( |0\rangle \) with probability \( |\alpha|^2 \) or to \( |1\rangle \) with probability \( |\beta|^2 \). The measurement process is not reversible as the state of the system collapses to 0 or 1, losing all memory of previous amplitudes \( \alpha \) and \( \beta \) [19].

Quantum gates are used to represent the operations on qubits, similar to the traditional classical circuits. For example, the quantum Walsh-Hadamard gate (\( H \)) is used to convert, e.g., \( |0\rangle \) to \( |+\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle) \), i.e. it gives a superposition state with equal probability for \( |0\rangle \) and \( |1\rangle \). Figure 1 illustrates a simple quantum circuit where the \( H \) gate is applied to a single qubit \( |0\rangle \) to produce \( \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle) \) as an output. The measurement step produces either 0 or 1 with equal probability. Finally, the qubit state collapses to the observed classical bit value.

A quantum register extends the qubit notation to higher dimensions. A quantum register \( |\psi\rangle \), comprising of \( n \) qubits, lives in a \( 2^n \)-dimensional complex Hilbert space \( \mathcal{H} \). While a classical register of size \( n \) is able to store a single value of the \( 2^n \) possibilities spanned by \( n \) classical bits, a quantum register is able to store all \( 2^n \) possibilities spanned by the qubits at the same time.

Gates can also be defined on multiple qubits. For example, Figure 2 illustrates the control gate. In a control gate, the operation (e.g. Not) is performed on the target wire, if and only if, the source line is \( |1\rangle \). This can be used to “entangle” qubits together. Entangled qubits are correlated with one another, in the sense that information on one qubit will reveal information about the other unknown qubit [19].

A quantum algorithm can be described using a quantum circuit, which is a combination of the quantum gates as shown in Figure 1. The input to the circuit is a number of qubits (in a quantum register) and the gates act on them to change the combined circuit state using superposition, entanglement, and interference to reach a desired output state that is a function of the algorithm output.

3 QUANTUM LOCALIZATION

ADVANTAGE: AN EXAMPLE

Fingerprinting-based localization systems provide a way to capture the relation between the received signal strength (RSS) coming from the different access points in the environment and user location [6, 34]. They work in two phases. The first is the offline calibration phase; where the RSS measurements of the different APs in the area of interest are collected at different discrete locations. This reflects the fingerprint of the APs at the different discrete locations. Then, in the online tracking phase, the received RSS from the different APs is matched to the fingerprint and the location in the fingerprint that is most similar to the heard signal becomes the estimated location.

Classical algorithms for fingerprint matching, e.g. [6, 34], usually run in \( o(MN) \). Using quantum parallelism, one can design an algorithm that runs in \( o(M\log(N)) \) [28], where \( M \) and \( N \) are the number of fingerprinting locations and the number of access points (APs) in the environment, respectively.

Figure 3 shows how the classical and quantum algorithms scale with the increase of the number of APs for a fixed number of fingerprint locations. The figure confirms the exponential saving in running time of the proposed quantum algorithm.

4 NEW DIRECTIONS

Building on the example we showed in the previous section, we now show the different directions of the use of quantum computing for localization and spatial algorithms.

4.1 Quantum Spatial Sensors

Although GPS is considered a ubiquitous outdoor localization technology, it has a number of shortcomings: its accuracy severely degrades/becomes unavailable in urban canyons; it does not work in important environments such as indoors,
Towards Quantum Computing for Location Tracking and Spatial Systems

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Figure 3: Asymptotic running time for the quantum algorithm compared to the classical one.

![Graph showing running time complexity vs. Number of APs (N)]

4.2 Quantum Device-free Localization

Device-free localization [4, 36] has been an active area of research. With the introduction of different quantum sensors that allow higher accuracy, precision, and sensitivity; new possibilities for device-free detection and sensing are unlocked. This includes, not only higher accuracy and range for the current applications, but also new device-free applications and services. For example, a high-sensitivity quantum magnetometer may be used, in a device-free manner, to look inside vehicles to see if a suspicious object is inside, e.g. a bomb, or estimate the car speed and model. These can also be extended to the recent energy-free sensing concept [16, 17, 35].

4.3 Secure Localization

By secure localization we refer to problems including location privacy and location verification. For example, by using quantum sensors, one can implement a stand-alone localization system that can run completely on the user device. This provides higher location privacy for the users. Given that the quantum state cannot be copied, according to the no cloning theorem [19], quantum algorithms may provide a more secure version of location verification that can counter classical attacks.

4.4 Theoretical Analysis

In this paper, we showed how quantum algorithms can have an advantage over classical algorithms in terms of required storage and running time. An active area of research in quantum computing is the quantum complexity theory that studies the complexity classes of quantum algorithms and their relation to classical counterparts [31]. Analyzing the complexity of the developed quantum algorithms for location tracking and spatial systems and obtaining performance bounds under different quantum complexity models is an important research direction.

4.5 Quantum Spatial Algorithms

Everyday, humans create large amount of data, especially data tagged with location information. Analyzing this massive amount of data is complex because of the limited computational power of classical computers. On the other hand, quantum computing may be able to provide significant advantage of storing and processing this data. Designing quantum spatial algorithms for processing large amounts of data as well as combining them with quantum machine learning techniques is an important open research direction [23, 24].

5 CONCLUSION

In this paper, we showed the potential of quantum computing in the area of location tracking and spatial systems. In particular, we showed that quantum fingerprinting algorithms can provide an exponential enhancement of both the space and running time complexity compared to their classical counterparts. We also explored the different directions for using quantum computing in localization and spatial systems.
REFERENCES


