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Advanced Electronics Practice

Shaping the long race in quantum communication and quantum sensing

While quantum computing is making headlines, two related technologies—quantum sensing and quantum communication—could reach the market earlier and potentially transform multiple industries.

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Quantum computing (QC), one of the most revolutionary technologies of our time, is about a decade away from widespread commercial application, based on our recent analysis. Less well known, but also important, are two related technologies that could become available much earlier: quantum sensing (QS) and quantum communication (QComm).

All quantum systems are incredibly complex, but their benefits are straightforward. QC exponentially decreases processing time, in many cases, making it possible to solve previously intractable problems. QS will allow for more accurate measurements and could offer higher accessibility than existing sensors (for instance, through device miniaturization). QComm will enable strong encryption protocols that could greatly increase the security of sensitive information, and it will also enable some critical quantum-computing functions (for more on the quantum phenomena underlying QC, QS, and QComm, see sidebar, "The technological leap").

With their unique capabilities, QC, QS, and QComm could transform multiple markets, including high-performance computing, navigation, pharmaceuticals, and medical imaging. Many tech giants and start-ups have already invested significantly in quantum technologies, with confirmed and announced deals for 2021 alone totaling about $2.1 billion. The majority of funding is flowing to QC initiatives, but a recent deal in the hundreds of millions for QComm, involving a special-purpose acquisition company, shows that the other quantum technologies are beginning to attract significant interest. We expect QComm and QS to attract even greater funding in the future, although it is unlikely to reach the same levels as QC because the markets for these technologies are smaller.

The race to lead the QS and QComm sectors will soon intensify as more competitors stake their bets. While much uncertainty persists, the companies most likely to persevere are those that translate quantum technologies into real-world applications with broad appeal. As with any nascent technology, however, investors may have difficulty identifying the technologies that fall into this category. Promising prototypes may encounter technical issues as R&D proceeds, or demand for

The technological leap

With quantum technologies, information is encoded in quantum bits (qubits). While the bits used in classical computing are binary, with a value of 0 or 1, qubits can assume values of 0, 1, or a combination of both. Qubits get their unique ability to assume multiple values because they rely on the quantum phenomenon known as superposition—the combination of two distinct physical phenomena of the same type (such as spin or wavelength) so that they coexist as part of the same event. Superposition enables new computing algorithms that can massively compress computation time. To give some idea of the improvement: in 2020, a Chinese research group used quantum computing to find a solution that would have taken a classical supercomputer 2.5 billion years to generate.

Since quantum systems are very sensitive to changes in the environment, quantum sensors could potentially detect minor changes in the environment that are beyond the grasp of ordinary sensors. With quantum communication, qubits communicate between distant locations, enabling parallel quantum computing. They also enable secure communication through a quantum phenomenon called entanglement—a process in which the measurement of one qubit instantly affects another, even if they are located far apart. Entanglement ensures that information cannot be intercepted as it passes from one qubit to another. While entanglement can also be used in quantum sensing, it is less fundamental to the technology, and some quantum sensors do not rely on this principle.

new products may fall short of initial expectations. Timing is also a major consideration for investors, since they must determine if they should place their bets before a technology has reached maturity or after it is commercialized.

While investing in quantum technologies carries an element of risk, the potential returns are high. By 2030, QS and QComm alone could generate $13 billion in revenues, and that amount could grow substantially in later years. To provide more clarity for investors as they chart a path forward, we explored the market landscape for QS and QComm, looking at both opportunities and challenges. We also identified critical questions about technology, risk, and market demand that investors can consider when allocating funds.

Overview of quantum technologies

QC, QS, and QComm may be used independently or in combination (Exhibit 1). When QC becomes commercially available, it may boost market demand for QComm and potentially for QS. For instance, QComm may be used to connect quantum computers to yield even more computing power through parallel processing.

Quantum simulation, another quantum technology, is sometimes referred to as special-purpose quantum computing. It involves simulating activities and their subsequent results within physical systems. Quantum simulation could find applications within research settings, such as solving mathematical optimization problems. The underlying technology required to perform quantum simulations is now available, but experts disagree about whether the simulations that are possible today offer a quantum advantage.

Quantum sensing

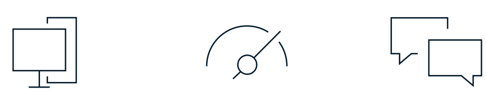
Quantum sensors can measure different physical properties, including temperature, magnetic field, and rotation, with extreme sensitivity. Their precision results from the sensitivity of quantum states to minor changes in the environment. Some quantum sensors can measure much smaller quantities than current sensors, while others provide better resolution when images are captured. Quantum sensors, once optimized and decreased in size, will also be able to measure data that can't be captured by current sensors, which are either too large to fit in the desired location or lack the required functionality.

There are two generations of quantum sensors. The first, which includes devices such as microwave atomic clocks and superconducting quantum interference devices (SQUIDs), has been available for decades. The second generation, which includes gravity sensors, nitrogen-vacancy (NV) sensors, and other innovations, is just emerging. Second-generation QS applications fall into at least eight applications, and they differ regarding maturity levels and market potential (Exhibit 2). The most competitive QS applications will include those for which no technology alternative exists. QS applications are also more likely to gain traction

Exhibit 1

Quantum technologies are now part of major research and investment.

Quantum technologies[1]



Quantum computing
Applying quantum mechanics to perform computations
- **Quantum simulation**
  Using quantum principles to improve modeling and simulations

Quantum sensing
Using quantum systems for high-precision measurement of physical quantities

Quantum communication
Transporting or exchanging of quantum-encoded information

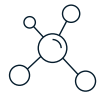
[1]Devices for applications that use quantum phenomena.

Exhibit 2

Quantum sensing has distinct advantages over alternative technologies in eight applications.

Applications for quantum sensing

Bioimaging
Neural sensing and heart imaging



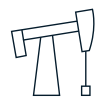
Spectroscopy
Imaging of molecular structures such as proteins

Communication
Signal receiving and amplification for radar communication; calibrating electrical standards to support 5G/6G

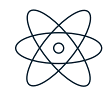
Navigation
Providing high-accuracy GPS; assisting with navigation inside buildings and underground

Environmental monitoring
Predicting volcanic disruption and measuring CO_2 emissions

Infrastructure monitoring
Monitoring mechanical stability and detecting leaks



Geographical surveying
Assisting with the location of oil and gas



Fundamental science
Accessing high-energy physics beyond the standard model

if they provide higher sensitivity than current sensors at a price that is comparable or less than alternative technologies.

Each second-generation QS application has different technical requirements, and some must overcome greater development hurdles than others. They also vary with regard to the advantages they convey. Within spectroscopy, for instance, quantum sensors could provide more accurate images of molecular structures, such as proteins, compared with the electron microscopes now available. QS applications can also capture images at the atom level, where artifacts are less likely to obscure the image. QS could also help to increase sustainability, as it enables monitoring of CO_2 emissions through higher precision and localized measurements.[1] Furthermore, energy consumption can be tracked and optimized when QS is integrated into smart buildings.

Quantum communication

QComm is designed to transfer encoded quantum information between distant locations through a quantum-communication network. It enables the following functions:

— *Full security.* QComm applications ensure complete protection when information is transferred between locations. The most popular method, quantum key distribution (QKD), involves assigning different people a confidential shared key for accessing data. Quantum encryption protocols are more secure than classical protocols, most of which will be broken once quantum computers gain significantly more computing power or more efficient algorithms. The most common form of classical encryption, RSA, will be vulnerable once the first relatively mature quantum computers are available. The classical encryption methods that might withstand the test of quantum computers are

[1] Currently, CO_2 emissions can be monitored with a precision of only up to one to three kilometers.

not optimal. Stephanie Wehner, the roadmap leader of the Quantum Internet and Networked Computing initiative at QuTech, noted, “We know mathematically that they never offer the same kind of security as QKD.”

— *Enhanced quantum-computing power.* QComm enables two important types of quantum processing. In parallel quantum processing, multiple processors are connected and simultaneously execute different calculations broken down from a larger problem. For instance, when calculating the route distance between 15 different cities, a classical computer would sequentially compute the length of the distance between each city and then total these amounts. In parallel quantum processing, the distance between each city would be calculated simultaneously. In blind quantum computing, QComm provides secure access to remote, large-scale quantum computers in the cloud. The remote computers do not have full access to the information that they are processing, to increase security.

The ultimate goal of QComm is to establish a quantum internet. Most areas will rely on fiber-optic networks, which are reliable but expensive, even though providers can build on existing fiber networks. The transmission of quantum information along short distances (less than 500 meters) is already possible via fiber-optic networks. Transmission over longer distances will not be feasible until researchers create fully functional quantum repeaters, which are devices that amplify signals and reduce the amount of information lost during transmission. We expect such quantum repeaters to become available over the next decade.

For some long-distance communications, such as transmissions across the ocean, QComm may rely on satellites to facilitate transmission. Satellites are not suitable for all locations, such as those with extreme weather conditions, however. The creation of satellite networks and the related ground infrastructure needed for QComm also presents many challenges that researchers are still trying to resolve.

The value chain for quantum sensing and quantum communication

We divided the QS and QComm markets into segments along the value chain to evaluate their current maturity and potential growth opportunities. Both markets have three segments in common:

— *Components.* This segment consists of the building blocks of hardware: lasers, detectors, cryostats, specialized fibers, and other technologies. Some companies already generate

Some organizations have already begun using quantum cryptography, and more could follow, especially in industries where secure communication is paramount.

significant revenue through sales of these products to research groups and start-ups; others offer products on the wider commercial market, although they have not yet developed push-button solutions that do not require complicated setup or assembly procedures.

— *Hardware.* QS hardware includes various devices, such as quantum atomic clocks and magnetometers, that measure physical properties using different quantum-bit (qubit) technologies (Exhibit 3). For instance, trapped-ion qubits measure time, rotation, and electric-field force; photonic qubits—those that transmit information as optical, rather than electrical, signals—can measure temperature and mechanical position. The QComm hardware market is much less fragmented because these applications all rely on photonics as their qubit technology. It is still very competitive, however, and some players are trying to build the fully functional quantum repeaters and satellite networks required for intercontinental communication.

— *Software.* For QS, software is used to integrate sensing technologies into applications and services, such as navigation systems. It now contains few players, since it depends on the availability of appropriate hardware. With QComm, most software involves quantum encryption for services such as email or bank transfers. The software segment is relatively immature, but various start-ups are attempting to scale up their operations. Some organizations have already begun using quantum cryptography, and more could follow, especially in industries where secure communication is paramount.

Beyond components, hardware, and software, the QComm value chain also includes two additional segments: quantum-network operations and quantum services. Network operators, which are now relatively few in number, provide and maintain large-scale quantum networks, including the necessary fiber cables. The need for their services will be largely limited until QComm hardware matures. Within quantum services, various

Exhibit 3

Quantum sensing uses six different technologies.

Quantum-sensing (QS) technologies

	Neutral atoms	**Trapped ions**	**Photonics**	**Spin qubits[2]**	**Superconducting circuits**	**Elementary particles**
Qubit[1] description	Changes to the energy level of an electron in warm vapor or a laser-cooled atom	Internal energy levels of ions trapped by electromagnetic fields	Two modes of a photon	Spin of one electron localized in a semiconductor quantum dot or insulator defect	Difference in Cooper pairs between two islands of a Josephson tunnel junction	Free electrons
Measured properties[3]	Magnetic field, frequency, acceleration, rotation	Time, rotation, electric field, force	Temperature, mechanical position	Magnetic field, electric field, temperature, pressure, rotation	Magnetic field, electric field	Magnetic field, photon density, gravity
Maturity for QS	Prototype	Theoretical evidence	Proof of concept	Proof of concept	Prototype	Proof of concept

[1]Quantum bit.
[2]Includes nitrogen-vacancy sensors.
[3]From P. Cappellaro, C. L. Degen, and F. Reinhard, "Quantum sensing," *Reviews of Modern Physics*, July 25, 2017, Volume 89.
Source: P. Cappellaro, C. L. Degen, and F. Reinhard, "Quantum sensing," *Reviews of Modern Physics*, July 25, 2017, Volume 89; McKinsey analysis

companies now provide advice on the technological and business aspects of QComm.

Overall, development and commercialization timelines for QS and QComm products are difficult to predict because progress depends on scientific breakthroughs. For instance, some quantum sensors have difficulty functioning outside the protected lab environment because they are so sensitive. Broad adoption also depends on device optimization, especially for size and weight. Reducing cost is also critical, since potential buyers may not want to pay a higher price for quantum technologies, despite their greater accuracy, if alternative solutions are available.

While many hurdles lie ahead, quantum solutions could generate substantial revenue over the next decade. They could even deliver value before device optimization occurs because researchers may discover many interim uses for currently available solutions. QComm could provide a safe internet connection between certain cities, for instance, while more widespread connections occur later. New use cases may emerge as the technology advances, such as a financial system that relies on quantum-secure currency. Since quantum states cannot be copied, hackers would not be able to create counterfeit money and the system would be extremely secure.

We attempted to determine how the market might evolve for QS and QComm, looking at a ten-year time horizon. For QS, our analysis focused on six of the most promising use cases: bioimaging, spectroscopy, navigation, environmental monitoring, geographic surveying, and fundamental science applications. In these areas alone, we estimate that QS could generate at least $5 billion in revenue by 2030.[2] This figure, while conservative, is still relatively low compared with the revenue expected from the much larger QC market. Although customer adoption may be slow, QS could eventually supersede classical technologies because of its increased accuracy and smaller size.

Revenue will depend, in part, on technology maturity. While many quantum sensors are at the prototype or proof-of-concept stage, some used for environmental and infrastructure monitoring are commercially available for various purposes, including leak detection in underground pipes and volcano monitoring. QS applications for fundamental-science applications, bioimaging, and navigation are relatively far along, and we expect that they will be commercialized and widely adopted over the next decade.

Prospects are also bright for QComm, partly because quantum computers are expected to break classical encryption protocols during that time. If researchers address the technical issues that limit widespread use, QComm could account for an estimated $8 billion in revenue by 2030. Eventually, the rise of quantum computers will unleash another new value pool for QComm because this technology is essential for both parallel and blind quantum computing.

The quantum-technologies marathon

Although uncertainty persists about the future QS and QComm markets, four core beliefs hold true (Exhibit 4):

— Competition will occur at the microvertical level in QS.

— Customer adoption will occur at different rates.

— All technologies can exist independently, but synergies may arise as quantum computing advances.

— There is still opportunity to get ahead of the curve.

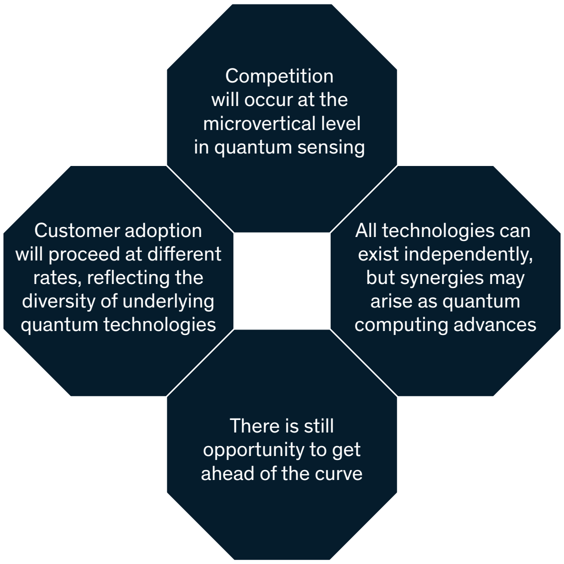
Competition will occur at the microvertical level in quantum sensing

For QS, no technology will emerge as dominant, since the best solution largely depends on the use

[2] For the six use cases that we examined, we assumed that those with the greatest potential would generate at least $1 billion in revenue annually, while those with less potential would generate about $500 million.

Exhibit 4

Four core beliefs hold true about the quantum-technologies market.



case. While neutral atoms and superconducting circuits are now the most mature, photonics and spin qubits are not far behind, and the remaining two technologies could quickly catch up. It is likely that some of the six technologies will coexist, although some will be much more dominant in certain applications than others.

Customer adoption will occur at different rates, reflecting the diversity of underlying quantum technologies

The adoption of quantum technologies will vary because of maturity levels and consumer interest. In some cases, an application may rapidly gain traction in one industry and attract little interest in other sectors because priorities differ. Military organizations, for instance, may first adopt navigation applications that can help troops accomplish critical missions. Other sectors in which high-precision navigation is important, such as automated agriculture, shipping, and automotive, may then follow. Regardless of industry, broad adoption of QS applications will not occur until stakeholders are convinced that the performance benefits justify their higher costs. For instance, scientists may continue to use electron microscopes, rather than QS spectroscopy applications, in situations where lower accuracy is acceptable.

Other factors that could affect adoption of QS applications include product characteristics, such as the ease of repair and replacement. For instance, companies might have sensors on container ships worldwide. To replace or repair these sensors, the company would need a global network of engineers, as well as parts readily available in all relevant locations.

With QComm, broad adoption of secure computing—the only application now available—will also depend on whether customers believe that the increased protection justifies the price. A psychological aspect is involved here, as some customers may perceive quantum technology as being the only safe alternative, even if other solutions are available. For instance, if a bank advertises that it uses QKD to protect accounts, some customers might be interested in their services, even though their current banks have extremely high security measures. And if QKD appears to be attracting many customers, additional banks may adopt this technology. Conversely, if it becomes clear that most customers are not concerned about having QKD protection, uptake may be limited.

Regulations could also cause interindustry variations in the uptake of quantum technology. For instance, medical applications might need to overcome major regulatory hurdles, causing healthcare agencies to delay implementation. Navigation applications, though also highly regulated, would face a lower regulatory bar that could contribute to more rapid uptake within automotive.

All technologies can exist independently, but synergies may arise as quantum computing advances

As quantum computing matures, it will not supplant QS and QComm. Instead, it will create synergies with

For quantum-technology players, long-term success involves carefully considering their current prototypes and determining which ones will enable real-life use cases.

them. More organizations will investigate QComm because of its ability to enhance QC, potentially increasing demand. Another synergy—while highly speculative—might involve sending information from a quantum sensor directly to quantum computers. If this process proves feasible, it could remove major bottlenecks for QC use cases that involve quantum artificial intelligence.

There is still opportunity to get ahead of the curve

Venture-capital investment in quantum technologies is surging. Many organizations—including governments and private-sector companies—are also beginning to investigate QS and QComm use cases, although investments are still much lower.

For quantum-technology players, long-term success will hinge on the strategies they develop now. The first step involves carefully considering their current prototypes and determining which ones will enable real-life use cases that appeal to a broad spectrum of potential customers. Without this diligence, their return on investment could be limited, even if the underlying technology breaks new ground. Companies should also devote some attention to practical issues, such as the process required to move from the first prototype to at-scale production, or the partnerships that could accelerate innovation or enhance their existing products. In some cases, companies in different industries may approach a quantum-technology player about a potential problem that they want to solve, and such partnerships could be mutually beneficial.

Leaders across industries and executives at large technology companies might want to consider forming partnerships with quantum start-ups and small to medium-size companies to identify real-life use cases and address them with currently available quantum-technology solutions. These partnerships could stimulate the essential development of end-to-end solutions that would benefit both parties. For example, quantum sensing is applicable to many industries, including chemicals, pharmaceuticals, and sustainable energy, and has numerous potential use cases. Businesses across industries can benefit from the talent that they gain when working with small to medium-size quantum companies. Businesses might even want to develop their own internal quantum talent. Moreover, big industry players can act as investors.

Investors must also make some quick moves, and they may gain an advantage by considering the following questions as they contemplate a company's quantum-technology offerings:

— Does the application have an alternative or competing technology? If so, will the increased sensitivity of QS justify the additional costs?

— What is the benefit of the application for specific customer segments?

— Which qubit technology is most suitable for the given application?

— What level of risk is appropriate to accept, and how long is it feasible to wait for a return on investment?

— Is it best to invest in components or applications for more mature technologies, such as some quantum sensors, or is it better to pursue potentially high-value applications for less mature technologies, such as quantum repeaters for long-distance QComm?

Quantum computing might lead to a technological revolution, but commercialization is still a distant prospect. In the meantime, both business leaders and investors can explore QS and QComm, two related technologies that have the potential to transform industries. The best companies will keep their investments grounded in reality by focusing on quantum technologies that have the potential to translate into real-life use cases with broad appeal.

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