Faster-than-light coordination for networked systems with quantum non-local games

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Abstract

Many networked systems rely on hashing and randomized algorithms for tasks such as load balancing, thereby avoiding the need for coordination or communication among participants on each request. However, purely random routing can lead to collisions and missed opportunities for beneficial colocation. Quantum entanglement enables participants to instantly make correlated decisions without communicating. We explore how this capability can expand the Pareto frontier of achievable performance in networked systems, presenting both positive and negative results. Notably, many of these advantages can be realized using small, currently available quantum devices that can often operate at room temperature.

CCS Concepts

• **Networks**; • **Theory of computation → Quantum computation theory**;

Keywords

Load balancing, quantum non-local games

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1 Introduction

With the imminent development of practical quantum computers, there has been interest in applying quantum technologies to networked and distributed systems. Some of the interest is driven by the potential for unconditionally secure quantum key distribution [24, 45]. However, most of the excitement rightly centers on the promise of exponential computational speedup in select applications, which has also influenced networking research [21, 34]. Realizing this vision however requires fully-fledged quantum computers with many qubits and long coherence times. Even the milestone of quantum supremacy—where a quantum computer performs some computation (no matter how artificial) that would be infeasible for the world's most powerful classical machines—remains debated and uncertain [5, 53].

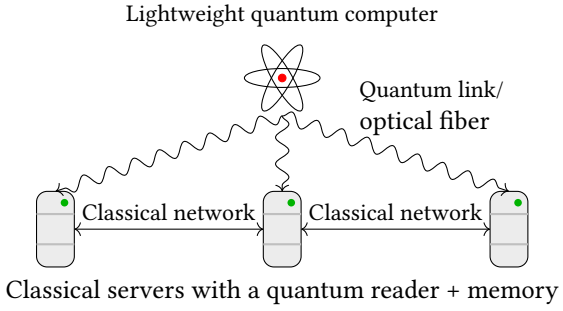

Figure 1: Proposed architecture

In contrast, this work focuses on an entirely different kind of quantum advantage, informally described as "*spooky action at a distance*" [22]. The central idea is that quantum entanglement enables correlations among multiple outputs that are stronger than what any classical system can achieve without communication, allowing faster-than-light correlation while still respecting causality (i.e., no faster-than-light communication). Importantly, leveraging this only requires a small number of qubits to demonstrate a measurable benefit – sometimes as few as two or three. Technology to exploit this is already mature and can even work at room temperatures with relatively inexpensive hardware.

This work envisions a *practical application* of this aspect of quantum entanglement. While the underlying physical phenomenon is well understood by now, a practical application of faster-than-light correlation remains elusive. We posit that a systematic effort in this direction may uncover a practically meaningful benefit in networked systems while enriching both the theory and experimental landscape of quantum non-local games with new applications.

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We focus on networked protocols that rely on randomization to make decentralized decisions. For instance, load balancers may randomly assign incoming requests to backend servers to avoid coordination overhead. However, some requests benefit from being co-located to exploit shared caches, in-memory objects, or parallel execution, while others require exclusive access to resources and perform best on idle servers. Meeting such preferences is difficult without explicit coordination among load balancers.

This kind of structured load balancing arises frequently in modern systems. GPUs, for example, aim to map requests referencing the same texture or memory region to the same Streaming Multiprocessor (SM) to maximize data locality, while distributing unrelated requests across SMs. Similarly, MapReduce-style pipelines exhibit comparable behavior when assigning tasks to reducers.

Although explicit communication could enable load balancers to respect these preferences, the associated latency is often prohibitive. Quantum non-local correlations offer a novel middle ground between full coordination and pure randomness: they reduce collision probability while still allowing instantaneous, independent decisions—achieving a form of coordination without communication.

Our architecture is shown in Figure 1: a central, lightweight quantum computer distributes entangled qubits to nodes across the network. Each node is equipped with a device that can measure its qubit in a configurable basis, and may also have the ability to store the qubit briefly before measurement. We show that quantum-assisted load balancers can outperform classical ones by choosing the appropriate bases.

We also present preliminary results exploring whether similar quantum advantages can be achieved in another setting: Equal-Cost Multi-Path (ECMP) routing. ECMP differs from the structured load balancing discussed above in a crucial way: not all participants are known ahead of time and there are no co-location constraints. Among N available servers, only some subset $M < N$ actively receive packets, and the goal is to allocate resources fairly among these M targets. The remaining servers are idle, and their behavior does not affect the outcome. This subtlety prevents reuse of techniques from affinity-sensitive load balancing from being directly applicable to ECMP routing. Our preliminary results prove that in such scenarios, N-way entanglement provides no advantage over M-way entanglement. We further conjecture that no quantum advantage exists for ECMP-style scenarios in general.

Quantum non-local games are an area of deep theoretical research, where many types of non-classical correlations have been explored [11, 18, 29, 41, 61]. We envision a collaboration between networking experts and quantum information theorists to uncover new theoretical games with practical application. After—or even during—this stage, experimental physicists can assess feasibility and translate promising ideas into real-world implementations. We believe the method shown in this paper is just the beginning. Future work will likely reveal many more primitives which can be packaged in system-level abstractions that systems designers can adopt without needing to understand the underlying quantum mechanics.

2 Background

Rather than give a comprehensive background on quantum computing, we introduce only the concepts needed to understand this paper. While we use mathematical notation for precise description consistent with literature, we also provide the high-level intuition wherever possible.

Single qubit system. To build intuition, consider a single qubit. A qubit should be considered a superposition of different states; in other words, a qubit is considered *in between* two states until it is *measured*. Measurement transforms (or collapses) the quantum state into a classical outcome (for example, 0 or 1) with different possibilities. Measurement is a destructive operation: once a qubit is measured, it is permanently the classical outcome that was observed. Measurement is done by projecting the qubit on a *basis vector*. The choice of basis vector is important due to two reasons: 1) The basis vector determines the classical outcome 2) Measurement is destructive, so we can't go back and re-measure with a different basis.

In more detail: like a classical bit, a qubit has two basic states, denoted $|0\rangle$ and $|1\rangle$. These are not just labels. They form the standard basis vectors of the 2-dimensional complex vector space $\mathbb{C}^2$, namely $[1, 0]^T$ and $[0, 1]^T$. Unlike a classical bit, a qubit can be in a superposition of these basis states. For example, the state $|\psi\rangle = (|0\rangle + |1\rangle)/\sqrt{2} = [1/\sqrt{2}, 1/\sqrt{2}]^T$ is "in between" 0 and 1 until it is measured. Measurement can happen in any orthonormal basis: $\{|\phi_0\rangle, |\phi_1\rangle\}$. The outcome will be 0 with probability $|\langle\phi_0|\psi\rangle|^2$, and 1 with probability $|\langle\phi_1|\psi\rangle|^2$, where $\langle\cdot|\cdot\rangle$ represents the dot product between the two complex vectors and $|\cdot|$ is the complex magnitude.

For instance, if $|\phi_0\rangle = |0\rangle$ and $|\phi_1\rangle = |1\rangle$, then measuring $|\psi\rangle = (|0\rangle + |1\rangle)/\sqrt{2}$ will yield 0 or 1 with equal probability. If instead $|\phi_0\rangle = (|0\rangle + |1\rangle)/\sqrt{2}$ and $|\phi_1\rangle = (|0\rangle - |1\rangle)/\sqrt{2}$ instead, measurement will always yield 0, since $\langle\phi_0|\psi\rangle = 1$ and $\langle\phi_1|\psi\rangle = 0$. That is, the state aligns exactly with the first basis vector, so the outcome is deterministic.

Entangled states. The only kind of quantum states this paper considers are generalizations of the "Bell pair": $(|00\rangle + |11\rangle)/\sqrt{2}$. This is a 2-qubit state generated by the quantum

computer in Figure 1, with one qubit sent to each of the two servers. In this notation, the first qubit (left side in both terms) is sent to the first server, and the second qubit is sent to the second server. However, the two qubits cannot be thought of as independent. When the first server measures its qubit—say in the standard basis $\{|0\rangle, |1\rangle\}$—it observes 0 or 1 with equal probability. Crucially, this measurement causes the second server's qubit to collapse to the corresponding state: if the first server measured i, the second server's state will collapse to $|i\rangle$. If the second server then measures in the same basis, its output will always match the first server's.

But the second server is free to choose a different measurement basis. For instance, suppose it uses the basis:

$$\left\{ \frac{1}{\sqrt{3}} |0\rangle + \frac{\sqrt{2}}{\sqrt{3}} |1\rangle, \frac{\sqrt{2}}{\sqrt{3}} |0\rangle - \frac{1}{\sqrt{3}} |1\rangle \right\}$$

Two cases arise. If the first server measured 0, the second will measure 0 with probability 1/3 and 1 with probability 2/3. If the first measured 1, these probabilities reverse. This creates correlations between the outcomes, even though no communication occurred; the marginal distribution at each server remains independent of what the other did (here, each server sees 0 or 1 with probability 1/2), but the *joint* distribution depends on their choice of measurement basis.

Note that we described the measurement process as if one server measured before the other. This is purely a mathematical convenience—the predictions of quantum mechanics do not depend on the order in which the measurements occur.

CHSH game. The CHSH game is the prototypical example of a non-local game where a quantum advantage exists [7, 17]. It was originally developed to experimentally rule out local hidden-variable theories in physics. Since then, quantum non-local games have developed into areas of intense theoretical and experimental study [10, 18, 38, 49, 51, 59, 65].

Consider two parties, Alice and Bob, with a referee, Charlie. Charlie sends bits x and y, each chosen uniformly at random. Alice and Bob respond with bits a and b, respectively. They win if $a \oplus b = x \wedge y$, where $\oplus$ denotes XOR. While Alice and Bob may choose any strategy, they are not allowed to communicate after receiving their inputs.[1] Classically, the best strategy is to always output $a = b = 0$, winning with probability 0.75 since $x \wedge y = 0$ in three out of four cases.

If they share a Bell pair, they can achieve a win probability of $\cos^2(\pi/8) \approx 0.85$, which is optimal under standard physical laws [66]. To achieve this, both players output the result of their measurement, where the basis for measurement depends both on the player and the input. Player x in input i measures in the basis $\cos\theta_i^x |0\rangle + \sin\theta_i^x |1\rangle$. Using straightforward algebra, one can find that the optimal values for θ_i^x are as follows:

- Alice uses $\theta_0^A = 0$ and $\theta_1^A = \frac{\pi}{4}$.
- Bob uses $\theta_0^B = \frac{\pi}{8}$ and $\theta_1^B = -\frac{\pi}{8}$.

Importantly, Alice and Bob's responses are *correlated* without any communication. Knowing Alice's input and output reveals nothing about Bob's input and output, and vice versa. In the optimal quantum strategy, each party still outputs 0 or 1 with equal probability.

The CHSH game was carefully designed to enable such correlation without communication. For example, the use of XOR in the win condition ensures that only the relation between a and b matters—whether they match or differ—not the specific values. This allows the outputs to remain uniformly random. Whether a similarly structured game can be designed for a practically useful application remains an open question.

Related Work. Non-local games have been extensively studied in theory to understand where quantum systems offer a provable advantage [18], to analyze specific problem instances such as multiparty [41] and deterministic strategies [11], and to generalize them through abstractions like semidefinite programming [61] and constraint satisfaction frameworks [29]. This growing body of work provides a foundation for identifying non-local games with potential for practical applications.

Entanglement is a cornerstone of many quantum applications, including quantum cryptography [24, 45], quantum networking [32, 62], and high-frequency trading schemes [20]. In the context of Byzantine agreement, quantum cryptographic primitives—such as quantum digital signatures—have been used to reduce the required number of nodes from the classical threshold of $3f + 1$ to $2f + 1$, achieving unconditional security [70]. Other protocols use entangled states to implement detectable or secure consensus with $3f + 1$ replicas, utilizing Bell pairs [4] or GHZ states [25].

3 Architecture and Hardware

Architecture. Figure 1 shows the proposed system architecture. A small quantum device generates entangled qubits and sends them to classical servers over a quantum network—most simply, a single fiber-optic cable. Each qubit can be encoded in the polarization of a photon: one orientation might represent a $|0\rangle$, another a $|1\rangle$, or even a superposition of both.

The servers remain mostly classical but are equipped with a quantum-enabled Network Interface Card (QNIC). A QNIC

[1] In physics experiments, this is enforced by requiring responses before light could travel between the parties. There, the goal is to test physical laws. Here, we care only about avoiding network communication latency.

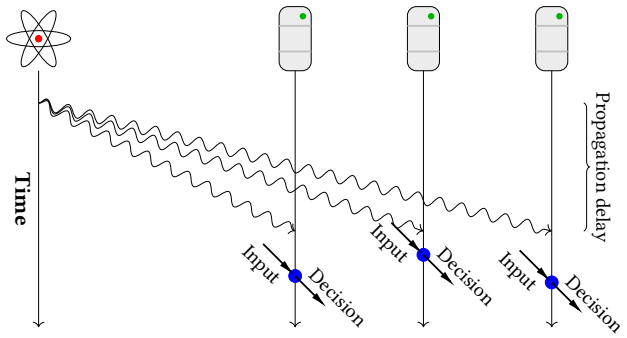


Figure 2: Since qubits are pre-shared, decisions can be made as soon as an input arrives at a server, without waiting for inter-server communication.

supports two main capabilities: it can measure an incoming qubit in a specified basis, and it can optionally store the qubit for a short duration (e.g., 100 μs to 1 ms). Both functions are feasible with existing hardware and can operate at room temperature [3, 46, 48, 63]. The servers are also connected with a "normal" classical network.

Timing. Figure 2 shows how quantum non-local games can enable faster-than-light correlation (but not communication). The quantum computer distributes a continuous stream of entangled qubits to the servers in advance [15, 36, 74]. As a result, each server can make its decision immediately upon receiving an input, without waiting for a network round-trip. The input could be a request or packet, arising remotely from external requests or from a process within the server. The decision might be which server or switch to forward it to, or whether to process it optimistically or wait for coordination over the datacenter network before proceeding.

A quantum advantage exists only when a quantum system produces correlations exceeding what is possible classically—even if classical machines pre-agree on a strategy and share randomness (e.g., by receiving classical random bits or sharing a seed for a pseudorandom function).

The QNIC must store the qubits during the interval between their arrival at the server and the moment a decision is made. Depending on the technology used, storage can be challenging. High-fidelity storage at room temperature has been achieved for 16–160μs [16, 37, 69]. In such cases, storage time can be reduced or eliminated entirely by arranging for the qubit to arrive *after* the input—so it is used immediately upon receipt. Note that while this sacrifices latency to eliminate storage, this strategy is still not limited by the speed of light, since the qubit can be sent much earlier in advance.

Is the hardware available today? Experimental tools for demonstrating correlations have existed since the earliest Bell inequality tests in the 1970s and early 1980s [6, 26]. These early experiments were conducted at room temperature, but the entanglement produced was extremely weak; sufficient to validate quantum mechanics, but not useful for more complex experiments or multi-party protocols.

This changed in the late 1980s and 1990s with the development of *Spontaneous Parametric Down-Conversion (SPDC)* [33, 60], which enabled high-quality entangled photon generation at room temperature. In this process, a nonlinear optical crystal is pumped with a laser, and occasionally a pump photon occasionally splits into two lower-energy photons—known as the signal and idler—which can be entangled in polarization, momentum, or time-energy.

Since then, SPDC-based entangled photons have become the workhorse for many quantum technologies including more rigorous tests of physical laws [27, 58], quantum metrology for ultra-precise measurements [28, 30, 42], quantum cryptography [24, 45], quantum networks [14, 32, 40, 62, 73], quantum teleportation [8, 9], and even early-stage quantum computers [35, 47, 50, 72]. These systems demonstrate the use of entanglement at room temperature, ranging from lab setups [28, 30, 42, 45], to long-distance fiber links [27, 32, 58, 71], to satellites [40, 73] (in the latter, Micius satellite operated at approximately "room" temperature, though the ground stations used cryogenic cooling). As of publication, SPDC crystals can be commercially purchased for USD 200-700 [19, 43]. Some experiments have gone beyond simple Bell pairs and generated 3-8 entangled photons at room temperature using SPDC [28, 67, 72]. Up to 18 entangled photons have been demonstrated in lab conditions, though without spatial separation [68]. While Bell pairs can be generated at rates of 10^4 to 10^7 pairs per second depending on the experimental setup, the rates of multi-photon entanglement drops off sharply, often by several orders of magnitude. While this paper focuses on room-temperature setups, cryogenic cooling can offer dramatically better performance in terms of photon rates, fidelity, and detection efficiency. Lastly, it is important to note that all quantum technologies operate with an error margin, which system designs must account for.

4 Leveraging Non-Local Games

We now describe how we leverage quantum non-local games to obtain an advantage for application-level load balancing. We also describe our preliminary results in trying to obtain an advantage for Equal Cost Multi-Path (ECMP) routing.

4.1 Application-level load balancing

Load balancing is a crucial feature of several modern networked systems [2, 54, 55]. At the simplest level, it involves getting a request and routing it to one of several available alternatives. Note that while all alternatives are acceptable

from a correctness viewpoint, performance is usually improved if related requests are routed to the same destination (due to caching). Routing unrelated requests to different servers also spreads the load more evenly among the available alternatives. Examples of load balancing in action today range from routing Google search requests [23] to routing invocations of serverless functions [1] to picking GPU SMs.

To avoid the overhead of coordination among load balancers, many systems simply forward requests to randomly chosen workers (servers, GPU SMs, etc.). Some use round-robin load balancing to mitigate the imbalance caused by randomness when task runtimes are relatively uniform [64]. Others adopt more informed strategies, such as the power of two choices [44], to achieve better load distribution.

Such strategies, however, struggle to account for co-location preferences. Consider two task types, C and E. Type-C tasks benefit from being *colocated* with other type-C tasks—e.g., due to shared caches, static in-memory objects, or because they can run in parallel efficiently (e.g., via GPU parallelism). In contrast, type-E tasks prefer *exclusive* access to resources and perform best when run in isolation.

CHSH game. This co-location problem maps directly to the CHSH game. Load balancers should route tasks to the same server if both receive type-C tasks; otherwise, they should route them to different servers. This aligns with the CHSH game logic, where inputs x and y are set to 1 if the corresponding load balancer receives a type-C task and 0 otherwise. The binary outputs determine which of the two servers each load balancer should send the task. Note, one party's output is flipped so that the balancers implement the condition $a \oplus b = \neg(x \wedge y)$ instead of $a \oplus b = x \wedge y$ ($\neg$ denotes the logical NOT).

XOR games. This idea generalizes to more than two task classes through the well-studied class of XOR games [18]. Here, task types are represented as vertices, and their affinity or disaffinity is captured by labeled edges that indicate whether tasks should be colocated. XOR games are so well understood that a polynomial-time algorithm exists to determine the quantum algorithm for a given graph [18]. In fact, most graphs with randomly labeled edges exhibit a quantum advantage, making it the typical case (see Figure 3). These games have also been extended to more than two players [12], corresponding to scenarios with more than two parties (here, load balancers), where the advantage is larger than in the two-party case [31]. The main limitation is that the outputs are binary, so load balancers can only choose between two servers. Nonetheless, our simulation below demonstrates that benefits can be obtained in systems with many load balancers and servers even with this limitation.

General games. Algorithms exist that can determine whether a quantum advantage is possible for an arbitrary finite game defined by a set of inputs to both parties, the corresponding output conditions for a "win", and the probability distribution over input combinations [39]. These algorithms evaluate whether a quantum non-local system with a given number of qubits can outperform any classical strategy. However, the problem is undecidable in general, and the algorithm may not terminate. Positive results are known in specific cases, such as XOR games and quantum graph coloring problems [13, 52, 57]. Future research should aim to identify additional classes of games that are applicable to systems problems.

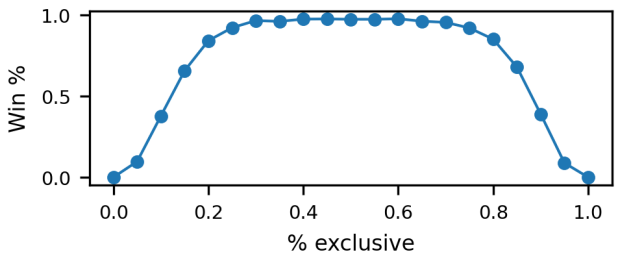


Figure 3: Probability that a quantum advantage exists for a randomly generated XOR game on a graph with 5 vertices, shown as a function of the probability that an edge is exclusive (computed using Toqito [56]). An exclusive edge means that when the two parties receive the connected vertices as inputs, they should output *different* bits (as opposed to the same bit). The probability of achieving a quantum advantage increases with the number of vertices. The dimensionality of entanglement required is bounded by $2^{\#\text{vertices}}$ [18]

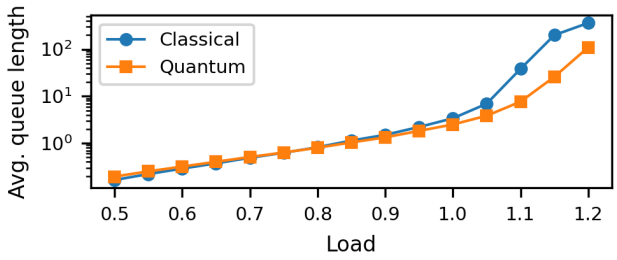


Figure 4: Simulation showing that quantum load balancing can reduce the average queuing delay.

Simulation study. We conduct a simple simulation to evaluate whether two-player CHSH games can provide an advantage in a system with N load balancers and M servers, particularly for large values of N and M. At each timestep, each load balancer receives either a type-C or type-E request with equal probability. They forward it to a server according to its load balancing algorithm. Servers can simultaneously process two type-C requests first, followed

by type-E requests, which are executed one at a time.[2] We measure average queue length as a function of system load, quantified by the ratio N/M, as shown in Figure 4.

In the classical strategy, each load balancer sends its request to a randomly selected server. In the quantum strategy, load balancers are paired. Each pair randomly selects a pair of servers in each round and uses the CHSH protocol: if both balancers receive type-C requests, they attempt to send them to the same server; otherwise, they send them to different servers.

Figure 4 shows that the knee point—where queue length begins to increase rapidly—occurs later in the quantum version. The figure reports results for $N = 100$, but the results depend primarily on the ratio N/M and remain largely consistent as N varies.

Caveats. Our simulation assumes a setting where task execution time is roughly equal to a round-trip time. If task execution were longer, load balancers that communicate could perform better. If execution were shorter, then at high load, multiple tasks could arrive within a single round-trip time. In that case, each load balancer could locally route all type-C tasks to a single server and distribute type-E tasks across others. A quantum advantage may still exist under such conditions, but it would likely be smaller. Further, one may consider classical and hybrid strategies that dedicate servers to type-C tasks, though these would not work if there are multiple subtypes of type-C tasks that do not like being mixed. Additionally, our simulation is intentionally simple and does not model caches, GPUs, or network behavior in detail. Its primary goal is to demonstrate that even basic two-party CHSH games—among the most physically realizable quantum protocols—can yield a measurable systems-level benefit and push the Pareto frontier of possible load-balancing strategies. Further work is needed to assess whether the quantum advantage can be robust and large enough to justify its cost.

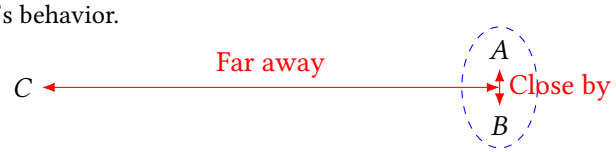
4.2 ECMP Routing

Consider N switches doing Equal Cost Multi-Path (ECMP) routing among $M < N$ paths. In theory, if at most M switches have packets to send, they could be assigned distinct paths to avoid contention. However, in practice, no switch knows which others have packets to send. Since communicating this information is expensive, path selection is typically randomized, either per-packet or per-flow.

We hoped that quantum non-local protocols could reduce the probability of collision below what is achievable by classical randomization. However, we proved a partial impossibility result that rules out a certain class of quantum protocols.

Specifically, one might imagine that enabling all N switches to share a globally entangled state could help coordinate their choices more effectively. But in the absence of communication, we show that such global entanglement offers no advantage over M-way entanglement.

The core idea relies on a standard proof trick from quantum information: we assume, without loss of generality, that some subset of the switches are placed far apart—so far that light-speed communication would take longer than the window in which path selection decisions must be made. For example, consider three parties A, B, C, of which only A and B receive packets. If, as shown below, C is far from A and B, then A and B must make decisions without knowledge of C's behavior.



The no-signaling principle implies that the joint distribution of outcomes observed by A and B cannot depend on any action taken by C; otherwise, faster-than-light communication would be possible, since A and B could exchange their outcomes and infer the influence of C before any signal from C could reach them.

Therefore, without loss of generality, we may assume C performs a measurement in advance, reducing the shared quantum state to a mixture of pairwise-entangled states between A and B. This proves that any coordination achievable with three-way entanglement must already be achievable with only pairwise entanglement. We additionally conjecture that pairwise entanglement offers no advantage in this problem. Combined with the proof above, the conjecture implies that quantum non-local games do not offer any advantage in reducing collisions for ECMP-style load balancing.

The same logic extends to larger networks: if only a subset of switches receive packets, any multi-partite entanglement involving inactive nodes is effectively useless under a no-communication constraint.

Lesson learned. The same proof technique applies broadly to settings where the quality of the outcome depends only on a subset of the participating parties. As a result, the most promising scenarios for finding quantum advantage in non-local games are those where the relevant subset of parties is fixed in advance (i.e., where all outputs matter regardless of input). This is the crucial difference between ECMP and application-level load balancing. In the latter case, the outputs of all parties matter irrespective of the input.

5 Conclusion and Future Work

This paper identified an application of the CHSH game—and, more broadly, XOR games—to load balancing scenarios where some tasks benefit from colocation while others

[2] The observed advantage is robust to other server execution strategies.

require exclusive access to resources. It also presented preliminary evidence that such quantum approaches can yield measurable end-to-end performance gains by generating correlations unattainable in classical systems.

We call for collaboration between researchers in networking and systems, and those in theoretical and experimental quantum computing. Cross-disciplinary efforts could uncover additional opportunities, potentially with greater practical relevance, where quantum correlations enhance system performance. These efforts should build on the field's extensive theoretical foundations [11, 18, 29].

Validating these benefits will require detailed systems experiments. Fortunately, such evaluations do not necessarily depend on real quantum hardware. Controlled studies can "cheat" by classically simulating quantum correlations when the full request stream is known in advance, as is common in testbeds, though not in production environments. Testbeds must also account for noise inherent to physical quantum systems.

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In memory of Prateesh Goyal

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