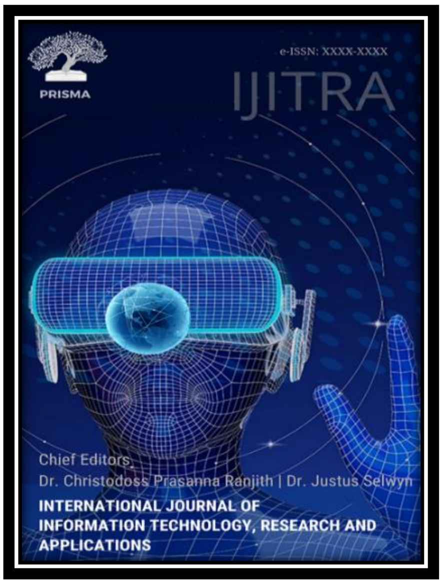

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Mimicking Photon Source Measurement with Quantum Digital Twin: A Framework for High-Quality Randomness

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ABSTRACT

Digital twins are virtual duplicates of tangible objects or systems. Within computer science, they play a pivotal role in simulating the software development life cycle, allowing for dynamic real-time testing and optimisation. Expanding beyond the confines of computing, sectors like manufacturing harness digital twins for predictive maintenance, ensuring operational efficiency, while healthcare employs them to replicate patient conditions, contributing to personalised treatment strategies. Through our efforts, we are crafting a digital twin of a renowned quantum mechanical attribute. This endeavour not only grants us insights into the inherent randomness intrinsic to quantum systems but also allows us to formulate a theoretical framework for a randomness generator using the model of this quantum digital twin. The outcomes, substantiated by results and plotted figures, substantiate our assertions, making a noteworthy impact on the advancement of authentic quantum random number generator sources. We are not just creating a novel avenue for generating randomness but pioneering a paradigm shift. Rooted in the digital twin model, our comprehensive framework affirms its efficiency when compared with the precision of the photon-based model.

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1. INTRODUCTION

The goal of making Digital copy enhances understanding, management, and decision-making throughout the lifecycle of physical assets. Industries leverage digital twins for diverse applications, such as optimising manufacturing processes, enabling predictive maintenance, and facilitating personalised healthcare treatment plans. In smart cities, digital twins aid urban planners in simulating and optimising various services. The Internet of Things (IoT) ecosystem integrates digital twins to enable real-time monitoring and control of connected devices[1], [2].

A quantum digital twin is a virtual embodiment of a quantum system, meticulously fashioned to replicate and simulate its physical counterpart's intricate behaviours, properties, and dynamics. Grounded in the principles of quantum mechanics, its purpose is to reproduce quantum processes and interactions within a digital realm faithfully. Recent strides in this field involve investigations into emulating quantum entanglement, superposition, and tunnelling phenomena within a digital framework. Researchers are actively refining algorithms and techniques to bolster the fidelity and precision of quantum digital twins[3]. These advancements open avenues for their application in quantum information processing, cryptography, and executing intricate simulations.

We aim to create a digital twin mirroring a specific physical experiment, specifically the photon light detection utilising a beam splitter[4]. Employing a Quantum Digital Twin (QDT) for this endeavour, we scrutinise diverse angles of the beam splitter's outcomes. Ultimately, we aim to construct a theoretical model for a randomness generator engineered to produce non-deterministic outcomes based on the insights gleaned from the digital twin analysis of the photon experiment[5].

2. LITERATURE REVIEW

The literature review explores the multifaceted realm of digital twins, elucidating their applications across industries and underscoring their pivotal role in enhancing decision-making, predictive maintenance, and operational efficiency[6]–[8]. In recent developments, quantum technology has surfaced as a transformative force for digital twins, offering heightened precision and fidelity in simulations, particularly within complex systems[9]–[11]. The review delves into the challenges and costs of maintaining natural quantum systems, positioning quantum digital twins as a promising, cost-effective alternative[12]. A thorough exploration of quantum mechanics also provides foundational insights crucial for comprehending quantum phenomena. Emphasising the critical importance of randomness, the review underscores how quantum mechanics inherently introduces true randomness, forming the basis for secure communication and algorithmic optimisation [13], [14]. The literature also scrutinises the potential of digital twin models to simulate quantum randomness. It comprehensively explains their efficacy in generating high-quality random numbers rooted in quantum principles [15], [16].

3. ORGANISATION

The article is structured as follows-

i. Section 4 – Define Digital Twin.

ii. Section 4.1 – Explains Quantum Digital Twin (QDT) and physical process of which digital twin is being make.

iii. Section 4.2 – How to generate randomness generation using the QDT model.

iv. Section 5 – Theoretical model of our proposed method using a code snippet based on QuTiP package.

v. Section 6 – Result using plots and tables.

vi. Section 7 – Conclusion.

4. DIGITAL TWIN

A digital twin is a virtual doppelgänger of its natural counterpart - an object, system, or process. Intricately crafted digitally, it faithfully mirrors the genuine article regarding its characteristics, behaviours, and intricate interplays. The genesis of the digital twin concept aligns with the surge in technological prowess, especially within the realms of the Internet of Things (IoT), simulation techniques, and the expansive domain of data analytics. At its core, a digital twin boasts distinctive traits:

a) Representation: Digital emulation draws from real-time data or historical records.

b) Interconnectedness: Seamless exchange of information unfolds, ensuring that alterations in the tangible realm reverberate in its digital doppelgänger and vice versa.

c) Monitoring and Analysis: Valuable insights, predictions, and avenues for enhancing the real-world object or system's performance and efficiency.

d) Simulation and Testing: Craft a virtual stage for simulating scenarios and stress-testing conditions without perturbing the physical entity.

4.1. QUANTUM DIGITAL TWIN

Zooming into the quantum frontier, the term ‘quantum digital twin’ emerges—a bespoke digital manifestation engineered to emulate the intricate dance of quantum systems and processes. Within this virtual realm, quantum states, interactions, and dynamics unfold, offering a panoramic view of the enigmatic quantum realm. This unravels complex phenomena and paves the way for applications like quantum information processing and serendipitous randomness generation.

In quantum mechanics, a photon light detection experiment employing beam splitters, photons are emitted from a source, typically a laser, and directed towards a beam splitter. The beam splitter, a fundamental optical component, divides the incoming photon beam into two distinct paths. Remarkably, due to the wave- particle duality inherent in quantum mechanics, each photon exists in a superposition, traversing both paths simultaneously. At the end of each path, detector screens capture the arrival of photons, creating an interference pattern when the paths are recombined. This interference pattern results from the quantum nature of photons, showcasing their ability to exhibit wave-like characteristics and the probabilistic outcomes inherent in quantum systems.

We replicate the photon light detection experiment employing beam splitters in quantum mechanics by leveraging the concept of a quantum digital twin. In this emulation, we utilise the Python package 'QuTiP' and 'mathpyplot' to construct a virtual representation of the quantum system[17]. The quantum digital twin encapsulates photons' wave-particle duality and beam splitters' behaviour. By applying qutip's functionalities, we simulate the superposition of quantum states, the propagation of photons through distinct paths, and the subsequent interference patterns on virtual detector screens. This computational approach allows us to explore and analyse intricate quantum behaviours, providing insights into quantum digital twins' potential applications and capabilities in replicating and understanding complex quantum experiments.

4.2. RANDOMNESS USING QDT

In quantum mechanics, randomness is inherent due to the probabilistic nature of quantum states. Quantum systems exhibit inherent uncertainty, and specific outcomes are determined by probabilities described by wave functions. The concept of superposition allows particles to exist in multiple states simultaneously, contributing to the unpredictability. When harnessed through techniques like quantum digital twins or measurements, this inherent randomness becomes a valuable resource for applications such as secure cryptography, where the unpredictability of quantum states enhances the security of communication protocols.

In our attempt to delve into the quantum experiment involving photon light detection and beam splitters, we aim to create a quantum digital twin replica using advanced quantum computing tools. Leveraging the Python package 'QuTiP', we construct a virtual representation that mimics the intricate behaviours of quantum particles in superposition and their interaction with beam splitters. Through this quantum digital twin, we seek to analyse how the inherent randomness derived from the experiment manifests in the simulated outcomes. This experiment will create potential applications of quantum digital twins in understanding and harnessing the inherent unpredictability within quantum mechanical processes, making a quantum random number generator that provides results without any predictable form and deterministic condition.

5. THEORETICAL FRAMEWORK OF QDT

This image sketches the structure of a quantum mechanical experiment utilising a beam splitter. The experiment comprises a single photon light source, introducing a fundamental quantum element. As the photon encounters the beam splitter, it undergoes a process of uncertainty, reflecting the intrinsic probabilistic nature of quantum states. The final stage involves two detectors strategically placed to measure the arrival of photons, capturing the outcomes and revealing the unpredictable nature inherent in quantum phenomena.

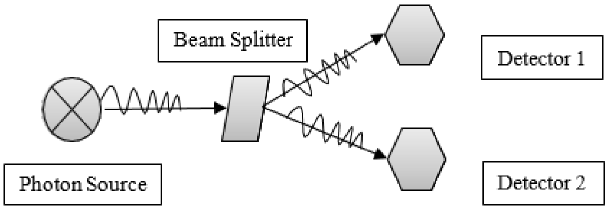

Figure 1: Structure of Photon sources detection using Beam Splitter

We employ Python to translate the quantum above mechanical experiment into the digital domain, explicitly utilising the ‘QuTiP’ package. Through this quantum computing tool, we meticulously construct a quantum digital twin, replicating the dynamics of the experiment. Leveraging the built-in methods of ‘QuTiP’, we develop a time evolution equation that encapsulates the behaviour of photons interacting with a virtual beam splitter. This equation serves as the foundation for our digital twin, mirroring the probabilistic nature and uncertainty inherent in the original quantum experiment, allowing for detailed analysis and simulation of equivalent quantum effects.

The provided code is a part of the more significant ‘twin_Photon_Beam_Splt’ function and is primarily responsible for simulating the evolution of a quantum system involving a beam splitter. Workflow of this specific part:

```
# Beam splitter Hamiltonian
        theta = angel
       H_bs = np.exp(1j * theta) * (tensor(a[0].dag(), a[1]) + tensor(a[0],
                                    a[1].dag()))

    # Initial state: single photon in mode 0
    psi0 = tensor(basis(2, 1), basis(2, 0))


     # Evolve the state through the beam splitter Hamiltonian
              times = np.linspace(start, end, steps)
    e_ops = [tensor(a[0].dag() * a[0], identity(2)), tensor(identity(2), a[1].dag()
                                     *     a[1])]
                        result = mesolve(H_bs, psi0, times, [], e_ops)
```

Code Snippet 1: Time evolution operator using QuTiP package

- *Beam Splitter Hamiltonian Calculation:*

"theta = angel": 'theta' is set equal to the parameter `angel` value.

"H_bs = np.exp(1j * theta) * (tensor(a[0].dag(), a[1]) + tensor(a[0], a[1].dag()))": Constructs the Hamiltonian ('H_bs') for a beam splitter using the input angle ('theta'). The Hamiltonian represents the evolution of the quantum system.

- *Initial State Preparation*:

"psi0 = tensor(basis(2, 1), basis(2, 0))": Initialises the initial quantum state ('psi0') as a tensor product of the first mode in an excited state (' basis(2, 1)') and the second mode in the ground state (' basis(2, 0)'). This represents a single photon initially in mode 0.

- *Time Evolution through the Beam Splitter:*

"times = np.linspace(start, end, steps)": Creates an array of time values (`times`) from `start` to `end` with `steps` points. This defines the time at which the quantum state will be evaluated during the evolution.

"e_ops = [tensor(a[0].dag() * a[0], identity(2)), tensor(identity(2), a[1].dag() * a[1])]": Defines the list of operators (`e_ops`) to calculate expectation values during the evolution. These operators represent the photon number operators for each mode.

"result = mesolve(H_bs, psi0, times, [], e_ops)": Uses the QuTiP `mesolve` function to evolve the initial state `psi0` through the beam splitter Hamiltonian `H_bs` at the specified time points. The result is stored in the variable `result`, which contains information about the state evolution and expectation values.

In summary, this part of the code calculates the Hamiltonian for a beam splitter, prepares an initial quantum state with a single photon, and then evolves this state through the beam splitter Hamiltonian at different time points. The 'result' variable contains information about the evolution, including the expectation values of photon counts in each mode at each time point.

6. RESULT AND ANALYSIS

The analysis section focused on the quantum simulation results obtained using the QuTiP library to model twin photons generated through beam splitters. Specifically, our investigation concentrated on varying the angle parameter of the beam splitter equation in the QuTiP code. The simulations were conducted across various angles, starting from 0 degrees and incrementing by 45 to 360 degrees. The time evolution was performed for sections ranging from 3 to 5, each with step increments ranging from 1100 to 4100. The obtained results provide insights into the behaviour of the twin photon system under different angular configurations and time intervals.

Our experimental quantum digital twin (QDT) generated distinct outcomes based on the specified parameters in the results and analysis section. Notably, the resulting plots from the QDT, created using the above values, are segregated into positive and negative categories. These designations align with our goal of randomness generation. The positive plots, corresponding to angles 45, 90, 180, 225, 315, and 360, present values conducive for further exploration as potential sources of desired quantum randomness. Conversely, the negative plots, associated with angles 0, 135, and 270, exhibit characteristics that may challenge effective randomness generation. This differentiation provides valuable insights into the nuanced impact of the beam splitter angle on the quantum digital twin's ability to yield desirable outcomes for randomness generation.

The positive plots corresponding to beam splitter angles 45, 90, 180, 225, 315, and 360 exhibit a compelling trend in the result and analysis section. These plots reveal that both detectors at either end consistently receive photon pulses at a rate exceeding 40%. This consistent observation suggests that the inherent randomness property of quantum mechanics introduces uncertainty in the photon detection process, resulting in a fixed percentage probability of photon arrival at any of the detectors. In this context, the reliable generation of photon pulses underscores the potential of leveraging quantum digital twins for controlled randomness generation with specific applications in mind.

In presenting the results in this paper, it is pertinent to note that the comprehensive experiment results are not included in their entirety due to their extensive nature. The sheer volume of data, especially in tabular format, can be overwhelming for readers. Therefore, a sensible approach has been adopted, where selective plots are showcased for their representativeness and clarity. This strategic selection ensures a concise yet informative representation of the experimental outcomes. We aim to balance clarity, conciseness, and the essential conveyance of pertinent experimental results by presenting critical findings through discerningly chosen plots.

Specific beam splitter angles were strategically chosen for the experimental design's negative (135 degrees) and positive (45 and 315 degrees) plot results. Each angle configuration underwent simulations with varying step counts (1100 and 4100 steps) within a time limit of 3 to 5 seconds. The resulting table's present probability values for each detector instance correspond to the chosen angles. To enhance clarity and conciseness, the tables encapsulate information for 5 instances each from the overall instances' initial, middle, and final sections. The plots, exemplified by the “Photon Counts over Time degree-45 timespan-3 steps-4100”, succinctly convey key experimental details, such as the beam splitter angle, runtime, and total instances considered.

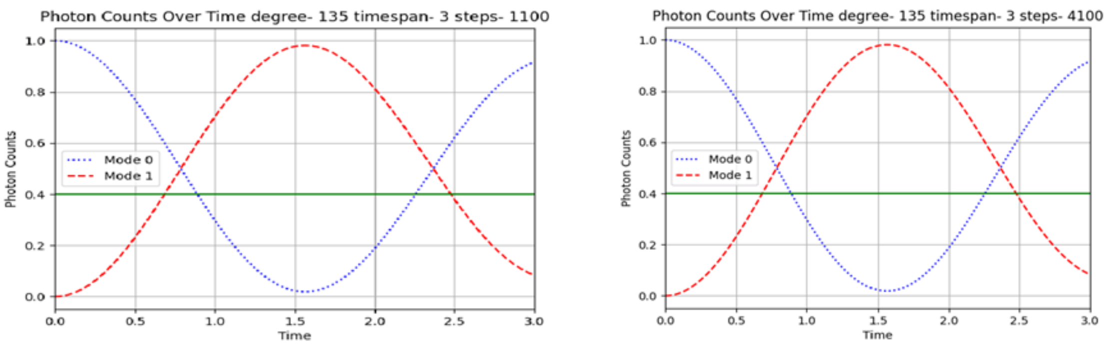

Figure 2: Beam splitter with Angel 135 Timespan 3 Steps 1100 and 4100

Instance	Time	Mode_0_Counts	Mode_1_Counts
1	0	1	0
2	0.002729754	0.999992548	7.45E-06
3	0.005459509	0.999970194	2.98E-05
4	0.008189263	0.999932938	6.71E-05
5	0.010919017	0.99988078	0.00011922
546	1.487716106	0.024417144	0.975582856
547	1.49044586	0.024018504	0.975981496
548	1.493175614	0.023634149	0.976365851
549	1.495905369	0.023264086	0.976735914
550	1.498635123	0.022908324	0.977091676
551	1.501364877	0.022566868	0.977433132
1096	2.989080983	0.914132748	0.085867252
1097	2.991810737	0.914797115	0.085202885
1098	2.994540491	0.915448812	0.084551188
1099	2.997270246	0.916087824	0.083912176
1100	3	0.916714138	0.083285862

Table 1: Beam splitter with Angle 135 Steps 1100

Instance	Time	Mode_0_Counts	Mode_1_Counts
1	0	1	0
2	0.000975848	0.999999048	9.52E-07
3	0.001951696	0.999996191	3.81E-06
4	0.002927543	0.99999143	8.57E-06
5	0.003903391	0.999984764	1.52E-05
2070	2.019029031	0.483177114	0.516822886
2071	2.020004879	0.483176925	0.516823075
2072	2.020980727	0.483176801	0.516823199
2073	2.021956575	0.48317674	0.51682326
2074	2.022932423	0.483176744	0.516823256
2075	2.02390827	0.483176812	0.516823188
4096	3.996096609	0.499452802	0.500547198
4097	3.997072457	0.499454702	0.500545298
4098	3.998048304	0.499456599	0.500543401
4099	3.999024152	0.499458491	0.500541509
4100	4	0.499460378	0.500539622

Table 2: Beam splitter with Angle 45 Steps 4100

Instance	Time	Mode_0_Counts	Mode_1_Counts
1	0	1	0
2	0.004549591	0.999979302	2.07E-05
3	0.009099181	0.999917212	8.28E-05
4	0.013648772	0.999813748	0.000186252
5	0.018198362	0.999668937	0.000331063
546	2.479526843	0.4755117	0.5244883
547	2.484076433	0.475702097	0.524297903
548	2.488626024	0.475891932	0.524108068
549	2.493175614	0.476081196	0.523918804
550	2.497725205	0.47626988	0.52373012

551	2.502274795	0.476457978	0.523542022
1096	4.981801638	0.500558028	0.499441972
1097	4.986351228	0.500552974	0.499447026
1098	4.990900819	0.500547943	0.499452057
1099	4.995450409	0.500542935	0.499457065
1100	5	0.50053795	0.49946205

Table 3: Beam splitter with Angle 315 Steps 1100

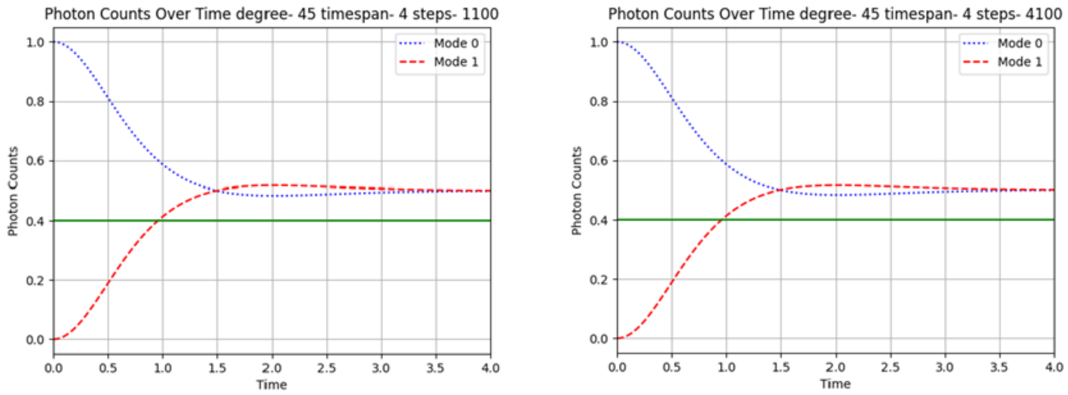

Figure 3: Beam splitter with Angel 45 Timespan 4 Steps 1100 and 4100

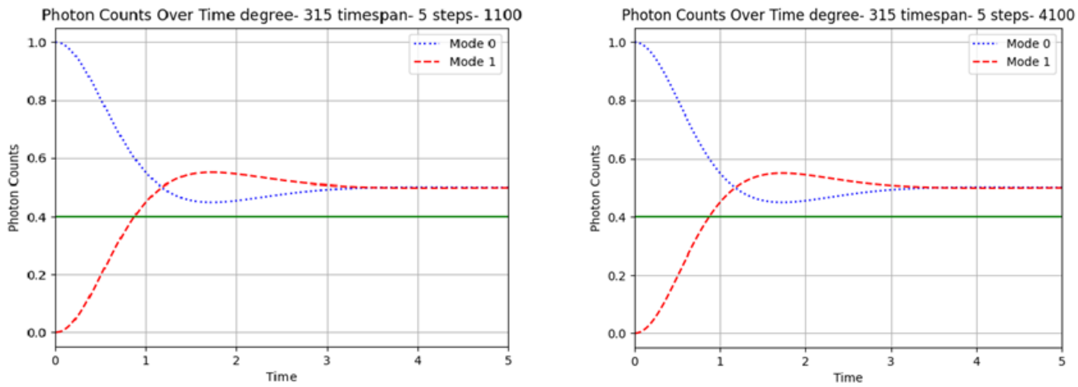

Figure 4: Beam splitter with Angel 315 Timespan 5 Steps 1100 and 4100

7. CONCLUSION

In conclusion, our quantum digital twin model, adept at mimicking the intricate process of physical photon light detection through beam splitters, emerges as a powerful and efficient tool for studying quantum phenomena without the need for elaborate experimental setups. Our exploration into various beam splitter angles reveals the nuanced impact on outcomes, emphasising that not all angles provide similar results. The positive plot results, demonstrating consistent and unpredictable photon detection, signify their potential as reliable sources of randomness. Building on this insight, our immediate future work entails the development of an actual random number generation tool utilising these positive plot results. Looking ahead, we recognise the plethora of other parameters within the quantum domain that merit further investigation, with QuTiP as a robust tool for this purpose. Our study contributes to the efficacy of quantum digital twin models. It paves the way for practical applications in randomness generation and allows continued exploration in the broader quantum landscape.

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	**Rounak Biswas**** Is an accomplished scholar with a Master's completed in 2019, specialising in Computer Science. He is dedicated to advancing knowledge in the field and pursuing a full-time PhD in Quantum Computation. Notably, he has been awarded a prestigious National Fellowship for Schedule Caste students, a testament to his commitment to excellence and significant contributions to the academic field. He has authored and published a research paper in a reputable journal. He further presented research findings at two international conferences, showcasing expertise in the intricate field of quantum computation. This further highlights our dedication to staying at the forefront of knowledge.
	**Dr. Utpal Roy** He holds a master's and Ph.D. in Mathematics from Visva-Bharati, followed by a tenure at Laval University in Quebec, Canada. Beginning as a Scientist Pool at IACS in Jadavpur, Calcutta, he later assumed the role of Assistant Professor in computer science at Visva-Bharati. His career also encompasses a Visiting Faculty position at Academia Sinica in Taipei, Taiwan, from 2002 to 2003. Appointed as a Professor at the Department of IT at Assam University Silchar in February 2008, he presently serves as a Professor and past Head of the Department of Computer and System Sciences at Siksha-Bhavana, Visva-Bharati, accumulating 28 years of teaching and research expertise.