Comment on "Quantum Clock Synchronization Based on Shared Prior Entanglement"

In a recent Letter [1], Jozsa, Abrams, Dowling, and Williams (hereafter referred to as the authors), outline a technique for using quantum nonlocality to synchronize remote clocks. It is quite possible that clock synchronization may be an excellent application of quantum technology. Indeed, the subject paper has already generated much useful discussion. However, the specific protocol outlined by the authors has several serious problems. In particular, while it is possible that such a protocol exists, the protocol put forth by the authors appears to require *a priori* knowledge of the same clock synchronization that it is attempting to achieve.

When discussing clock synchronization it is critical to clearly define whether the synchronization refers to frequency or time. When two clocks are phase locked ("ticking in synchrony") then their frequencies are synchronized (i.e., "syntonized")—no absolute time information is involved. However, time synchronization requires a well-defined common origin of phase. The authors initially refer to syntonization ("an estimate of the clock phase $\Omega t \bmod 2\pi$"). Later they are interested in time synchronization ("shared origin of time"). We will show that the reasoning used in either case is circular.

In the authors' proposed protocol, two observers, Alice and Bob, whose clocks are to be synchronized, reside in separate locations and share an ensemble of entangled states. The authors require that these separated quantum systems all "undergo identical unitary evolutions," a condition that is tantamount to the ability to build perfect frequency standards. [The paper also contains errors in its description of how atomic clocks work, most notably Eq. (2) which contains no local oscillator phase information and the wrong time dependence [2,3].] Furthermore, the protocol requires Alice and Bob to use perfect frequency standards (required in addition to the identical unitary evolutions) to interrogate their respective states with a known fixed phase relationship in order to determine what that relationship is—a circular argument.

The authors themselves point out this flaw and address it by adding a second frequency. The previous single frequency protocol is now applied at two frequencies, Ω_1 and Ω_2. The assumption is made that at some time, t_0 (in the paper $t_0 = 0$ as seen by Alice), there is an unknown initial phase difference δ between Alice's and Bob's systems of both entangled particles and the required perfect frequency standards, and in addition that δ is *the same* for both systems. That is, Bob's $\Omega_{1(2)}$ oscillator is offset from Alice's $\Omega_{1(2)}$ oscillator by $\delta_{1(2)}$ and that $\delta_1 = \delta_2 = \delta$. The protocol then proceeds as before except that instead of looking at state oscillations in only one frequency, the beats between the two frequencies are observed with the statement that the beat note is independent of the unknown phase. While this is true, the statement is mathematically trivial because a knowledge of the frequencies Ω_1 and Ω_2 (as required for operation of the protocol at each frequency) along with the fact that $\delta_1 = \delta_2$ determines t_0 by simple algebra. No protocol is required. The authors are implicitly assuming a knowledge of t_0 (by stating that $\delta_1 = \delta_2$) to determine this same quantity—again, circular reasoning, and the protocol, with or without two frequencies, will fail to achieve either frequency or time synchronization without first assuming knowledge of the desired information. We would like to stress that we are not suggesting that a protocol to accomplish quantum clock synchronization does not exist. Rather we simply wish to point out that this specific protocol has problems.

It seems possible that the phase-sensitive nature of atomic clocks and Ramsey interferometers sets quantum clock synchronization schemes apart from other problems in quantum information such as quantum key distribution [4]. Any attempt to resolve clock phase ambiguity classically within a "quantum" protocol must be considered inherently no better than classical time synchronization methods. If a quantum clock synchronization protocol is to improve on these classical techniques, the phase information *must* be transported quantum mechanically and in such a way that it avoids "classical" perturbations.

In summary we believe that the possibility of synchronizing remote clocks via quantum mechanical means is an interesting and potentially fruitful area of study, but that the protocol described in [1] is circular because it requires *a priori* knowledge of time synchronization in order for the protocol to work.

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