Delphi 4A

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Abstract

The design of Delphi 4 is modified in order to remove a timing error. Delphi 4A is a superluminal optical communication system.

1. Introduction

This system uses nonlocal, two-photon interference like that described in [1].

A representation of the system is shown in Figure 1. The system is composed of a Source (Src), a Transmitter (Tx), and a Receiver (Rx).

The optical path length from the Source to the Transmitter is somewhat less than the optical path length from the Source to the Receiver. The Source, Transmitter, and Receiver are all assumed to be stationary.

To simplify the description of this system, the effects of optical filters, detector quantum efficiency and dark counts, and most other potential losses are not included in the following discussion.

2. Notation

In the following discussion, both probability amplitude and probability will be calculated. As an example:

$$P[D1,D5,(\Delta)] = \left|pa[D1,D5,(\Delta)]\right|^2$$

In the above, pa[D1,D5,(Δ)] is the probability amplitude for the detection of a signal photon of a down-converted pair in detector D1 in the Transmitter, and the detection of the idler photon of the pair in detector D5 in the Receiver. The time parameter (Δ) is the time between the detection of the signal photon in the Transmitter and the detection of the idler photon in the Receiver.

P[D1,D5,(Δ)] is the probability for the same detection events.

Both intensity and amplitude variables are used in the following. As an example, for amplitude beam splitter ABS1:

$R_1 = |r_1|^2$, $T_1 = |t_1|^2$ and $R_1 + T_1 = 1$

In the above, R_1 is the intensity reflectance, T_1 is the intensity transmittance, r_1 is the amplitude reflection coefficient, and t_1 is the amplitude transmission coefficient of ABS1.

3a. Source

The Source (Src) contains a single-mode, continuous wave (cw) pump laser (LSR), a periodically-poled lithium niobate crystal (PPLN), a long pass dichroic mirror (DM), a polarizing beam splitter (PBS1), and a beam stop (Stp).

Laser LSR has a stable output, and the coherence length of the pump photons from LSR is greater than 200 meters.

The PPLN crystal is temperature-controlled, and is set to allow collinear, degenerate, type II spontaneous parametric down-conversion (SPDC). On average, one of every 10^6 of the photons from pump laser LSR is annihilated in a SPDC event that creates a signal and idler pair of photons. The signal photon is horizontally (H) polarized, and the idler photon is vertically (V) polarized.

Photons from pump laser LSR that are not down-converted in the PPLN are reflected at long pass dichroic mirror DM and are incident on beam stop Stp.

Polarizing beam splitter PBS1 is set to transmit incident H polarized photons and to reflect incident V polarized photons.

The longer wavelength signal and idler photons exit from the PPLN and are transmitted through DM. The H polarized signal photons are then transmitted through PBS1 and travel to the Transmitter (Tx). The V polarized idler photons reflect at PBS1 and travel to the Receiver (Rx).

3b. Transmitter

The Transmitter (Tx) contains a Pockels cell (PC), one polarizing beam splitter (PBS2), four amplitude beam splitters (ABS1-ABS4), six mirrors (m1-m6), and three detectors (D1-D3). The fast detectors are capable of photon counting.

The Pockels cell (PC) may be used to rotate the polarization direction of a signal photon. If the PC is turned off, an H polarized photon will remain H polarized when it exits from the PC. If the PC is turned on, an H polarized photon will be V polarized when it exits from the PC.

Polarizing beam splitter PBS2 is set to transmit incident H polarized photons and to reflect incident V polarized photons.

The amplitude beam splitters may be partially-silvered plate beam splitters. Beam splitter ABS4 is a “50/50” amplitude beam splitter. The characteristics of the beam splitters are:

$R_1 = |r_1|^2$; $T_1 = |t_1|^2$
$R_2 = |r_2|^2$; $T_2 = |t_2|^2$
$R_3 = |r_3|^2$; $T_3 = |t_3|^2$
$R_4 = |r_4|^2 = 0.50$; $T_4 = |t_4|^2 = 0.50$

Amplitude beam splitters ABS1 and ABS2 and two mirrors (m1 and m2) form an optical circulator (OC). The time required for a photon to make one cycle around through the OC from ABS1 to ABS2 and then travel via reflection at the two mirrors back to ABS1 is equal to X.

The fixed time X should be much longer than the coherence time of a signal (or idler) photon but should also be much shorter than the coherence time of a photon from pump laser LSR in the Source.

Path lengths through the OC are adjusted so that the net phase difference from input to output depends on the reflections at the mirrors and the reflections (or transmissions) at the beam splitters [2].

Amplitude beam splitters ABS1, ABS2, and ABS3 and two mirrors (m3 and m4) form the first balanced Mach-Zehnder interferometer (FMZ).

Amplitude beam splitters ABS3 and ABS4 and two mirrors (m5 and m6) form the second balanced Mach-Zehnder interferometer (SMZ).

Path lengths through the two balanced MZs are adjusted so that the net phase difference from input to output depends on the reflections at the mirrors and the reflections (or transmissions) at the beam splitters [2].

Requirements for proper system operation:

$$|r_3| >> |t_3|$$

$$|(r_1\ t_2\ r_3)| > |(t_1\ t_3)|$$

$$|(t_1\ t_2\ r_3) + (r_1\ t_3)| > |(r_1\ r_3) - (t_1\ t_2\ t_3)|$$

$$|t_1(r_3 + t_3)| = |(r_1\ t_2)(r_3 - t_3)|$$

3c. Receiver

The Receiver (Rx) contains two amplitude beam splitters (ABS5 and ABS6), two mirrors (m), and two detectors (D4 and D5). The fast detectors are capable of photon counting.

The amplitude beam splitters may be partially-silvered plate beam splitters. Both ABS5 and ABS6 are "50/50" amplitude beam splitters. The characteristics of the beam splitters are:

$$R_5 = |r_5|^2 = 0.50 \; ; \; T_5 = |t_5|^2 = 0.50$$
$$R_6 = |r_6|^2 = 0.50 \; ; \; T_6 = |t_6|^2 = 0.50$$

Amplitude beam splitters ABS5 and ABS6 and the two mirrors (m) are arranged to form an unbalanced Mach-Zehnder interferometer (MZ). Unbalanced MZ provides a short path and a long path between ABS5 and ABS6 for idler photons.

The path lengths through the MZ are adjusted so that the net phase difference from input to output for a given path depends on the reflections at the mirrors and the reflections (or transmissions) at the beam splitters [2].

The time difference between the time an idler photon may be incident on detector D4 (D5) via the short path, and the time the photon may be incident on detector D4 (D5) via the long path through the MZ is equal to X.

The fixed time X should be of sufficient duration to allow the short path and the long path to be temporally distinct. Time X should be much longer than the coherence time of an idler (or signal) photon but should also be much shorter than the coherence time of a photon from pump laser LSR in the Source.

Note: To facilitate the following descriptions, it is assumed that there are an integer number of wavelengths between the Source and the Transmitter, and also an integer number of wavelengths between the Source and the Receiver.

4a. Binary Zero

To send a binary zero from the Transmitter to the Receiver, Pockels cell PC in the Transmitter is turned off.

The idler photon of a down-converted pair that is created in the PPLN exits from the Source and travels to the Receiver. The signal photon of the pair exits from the Source and travels to the Transmitter.

At the Transmitter, the H polarized signal photon passes through the PC. Since the PC is off, the signal photon remains H polarized when it exits from the PC. The photon travels to and passes through PBS2 and is then incident on detector D1. In the binary zero case, signal photons do not reach ABS1 in the Transmitter.

At the Receiver, the V polarized idler photon passes through either the short path or the long path through the MZ and is incident on either detector D4 or detector D5.

If the signal photon of a down-converted pair travels from the Source to the Transmitter and is detected in detector D1, and the idler photon of the pair travels to the Receiver, passes through the short path through the MZ, and is detected in either detector D4 or D5, then the time between the detection of the signal photon in the Transmitter and the idler photon in the Receiver is equal to τ. Note that $\tau >> X$.

If the time difference between the detection of a signal photon in the Transmitter in detector D1, and the detection in the Receiver of the idler photon of the down-converted pair in either detector D4 or D5 is equal to τ, then there is no ambiguity as to which paths the photons travelled.

The signal photon travelled directly to detector D1 in the Transmitter, and the idler photon travelled via the short path through the MZ and was then incident on either detector D4 or D5 in the Receiver. The probability amplitudes and probabilities for this are:

$pa_0[D1,D4,(\tau)] = [1][it_5t_6]$

$P_0[D1,D4,(\tau)] = |pa_0[D1,D4,(\tau)]|^2 = T_5T_6 = 0.25$

$pa_0[D1,D5,(\tau)] = [1][-t_5r_6]$

$P_0[D1,D5,(\tau)] = |pa_0[D1,D5,(\tau)]|^2 = T_5R_6 = 0.25$

If the time difference between the detection of a signal photon in the Transmitter in detector D1, and the detection in the Receiver of the idler photon of the down-converted pair in either detector D4 or D5 is equal to $(\tau+X)$, then there is no ambiguity as to which paths the photons travelled.

The signal photon travelled directly to detector D1 in the Transmitter, and the idler photon travelled via the long path through the MZ and was then incident on either detector D4 or D5 in the Receiver. The probability amplitudes and probabilities for this are:

$pa_0[D1,D4,(\tau+X)] = [1][ir_5r_6]$

$P_0[D1,D4,(\tau+X)] = |pa_0[D1,D4,(\tau+X)]|^2 = R_5R_6 = 0.25$

$pa_0[D1,D5,(\tau+X)] = [1][+r_5t_6]$

$P_0[D1,D5,(\tau+X)] = |pa_0[D1,D5,(\tau+X)]|^2 = R_5T_6 = 0.25$

The probabilities for the detection of idler photons in detectors D4 and D5 in the Receiver in the binary zero case are:

$P_0[D4] = 0.25 + 0.25 = 0.50$

$P_0[D5] = 0.25 + 0.25 = 0.50$

4b. Binary One

To send a binary one from the Transmitter to the Receiver, Pockels cell PC in the Transmitter is turned on.

A down-converted pair of photons that is created in the PPLN exits the Source. The H polarized signal photon travels to the PC in the Transmitter, and the V polarized idler photon travels to the MZ in the Receiver.

The optical path length from the Source to the Transmitter is somewhat less than the optical path length from the Source to the Receiver. This ensures that almost every signal photon of a down-converted pair will be incident on a detector in the Transmitter before the idler photon of the pair reaches the Receiver.

At the Receiver, the V polarized idler photon passes through either the short path or the long path through the MZ and is incident on either detector D4 or detector D5.

At the Transmitter, the H polarized signal photon of the pair passes through the PC. Since the PC is on, the polarization direction of the signal photon is rotated and the photon is V polarized when it exits from the PC. The now V polarized signal photon travels to and reflects at PBS2 and then travels to beam splitter ABS1.

I) The V polarized signal photon may reflect at ABS1 and travel via reflection at mirror m4 to ABS3. The photon may then pass through ABS3 and travel to mirror m5.

Alternately, the signal photon may pass through ABS1, travel to and pass through ABS2, then travel to and reflect at mirror m3 and travel to ABS3. The photon may then reflect at ABS3 and travel to mirror m5.

These two possible paths for the signal photon are set equal in optical path length, so the signal photon arrives at mirror m5 with probability amplitude:

$pa_1(m5,0) = -i[(r_1\ t_3) + (t_1\ t_2\ r_3)]$

The photon reflects at mirror m5 and travels to ABS4.

Initially, the V polarized signal photon may reflect at ABS1 and travel via reflection at mirror m4 to ABS3. The photon may then reflect at ABS3 and travel to mirror m6.

Alternately, the signal photon may pass through ABS1, travel to and pass through ABS2, then travel to and reflect at mirror m3 and travel to ABS3. The photon may then pass through ABS3 and travel to mirror m6.

These two possible paths for the signal photon are set equal in optical path length, so the signal photon arrives at mirror m6 with probability amplitude:

$pa_1(m6,0) = +[(r_1\ r_3) - (t_1\ t_2\ t_3)]$

The photon reflects at mirror m6 and travels to ABS4. Path lengths are set so that the signal photon component from mirror m5 and the component from mirror m6 arrive at ABS4 at the same time.

Since both components are of the same signal photon, one-photon interference occurs at ABS4. The probability amplitude incident on detector D3 is:

$$pa_1(D3,0) = +i[(r_1\ t_3) + (t_1\ t_2\ r_3) + (r_1\ r_3) - (t_1\ t_2\ t_3)]/[\surd(2)]$$

$$= +i[(r_1(r_3 + t_3)) + ((t_1\ t_2)(r_3 - t_3))]/[\surd(2)]$$

The probability amplitude incident on detector D2 is:

$$pa_1(D2,0) = +[(r_1\ t_3) + (t_1\ t_2\ r_3) - (r_1\ r_3) + (t_1\ t_2\ t_3)]/[\surd(2)]$$

$$= +[((t_1\ t_2)(r_3 + t_3)) - (r_1(r_3 - t_3))]/[\surd(2)]$$

If the signal photon is incident on either detector D3 or detector D2, then all other components of this signal photon immediately cease to exist.

II) Also, the signal photon may initially pass through ABS1, travel to and reflect at ABS2, and then travel around through the OC via reflection at mirrors m1 and m2, and return to ABS1.

The signal photon may then reflect at ABS1, travel to and pass through ABS2, then travel to and reflect at mirror m3 and travel to ABS3. The photon may then reflect at ABS3 and travel to mirror m5.

Alternately, after making one cycle around through the OC, the signal photon may pass through ABS1, travel to and reflect at mirror m4 and travel ABS3. The photon may then pass through ABS3 and travel to mirror m5.

These two possible paths for the signal photon are equal in optical path length, so the signal photon arrives at mirror m5 with probability amplitude:

$$pa_1(m5,1) = -i[(t_1\ r_2\ r_1\ t_2\ r_3) - (t_1\ r_2\ t_1\ t_3)]$$

Note that, if the signal photon arrives at mirror m5 with probability amplitude $pa_1(m5,1)$, then it arrives at mirror m5 after it would have arrived with probability amplitude $pa_1(m5,0)$ by a time equal to X.

The photon reflects at mirror m5 and travels to ABS4.

Initially, the signal photon may pass through ABS1, travel to and reflect at ABS2, and then travel around through the OC via reflection at mirrors m1 and m2, and return to ABS1.

The signal photon may then reflect at ABS1, travel to and pass through ABS2, then travel to and reflect at mirror m3 and travel to ABS3. The photon may then pass through ABS3 and travel to mirror m6.

Alternately, after making one cycle around through the OC, the signal photon may pass through ABS1, travel to and reflect at mirror m4 and travel ABS3. The photon may then reflect at ABS3 and travel to mirror m6.

These two possible paths for the signal photon are equal in optical path length, so the signal photon arrives at mirror m6 with probability amplitude:

$$pa_1(m6,1) = -[(t_1\ r_2\ r_1\ t_2\ t_3) + (t_1\ r_2\ t_1\ r_3)]$$

Note that, if the signal photon arrives at mirror m6 with probability amplitude $pa_1(m6,1)$, then it arrives at mirror m6 after it would have arrived with probability amplitude $pa_1(m6,0)$ by a time equal to X.

The photon reflects at mirror m6 and travels to ABS4. Path lengths are set so that the signal photon component from mirror m5 and the component from mirror m6 arrive at ABS4 at the same time.

Since both components are of the same signal photon, one-photon interference occurs at ABS4. The probability amplitude incident on detector D3 is:

$$pa_1(D3,1) = +i[(t_1\ r_2\ r_1\ t_2\ r_3) - (t_1\ r_2\ t_1\ t_3) - (t_1\ r_2\ r_1\ t_2\ t_3) - (t_1\ r_2\ t_1\ r_3)]/[\surd(2)]$$

The probability amplitude incident on detector D2 is:

$$pa_1(D2,1) = +[(t_1\ r_2\ r_1\ t_2\ r_3) - (t_1\ r_2\ t_1\ t_3) + (t_1\ r_2\ r_1\ t_2\ t_3) + (t_1\ r_2\ t_1\ r_3)]/[\surd(2)]$$

With: $t_1(r_3+t_3) = (r_1 t_2)(r_3-t_3)$ and $r_3>t_3$:

$$pa_1(D3,1) = 0$$

$$pa_1(D2,1) = +\{[((t_1\ r_1\ t_2\ r_2)(r_3 + t_3)) + ((t_1^2\ r_2)(r_3 - t_3))]/[\surd(2)]\}$$

If the signal photon is incident on detector D2 with probability amplitude $pa_1(D2,1)$, then it is incident after it would have been incident on detector D2 with probability amplitude $pa_1(D2,0)$ by a time equal to X.

III) The signal photon may initially pass through ABS1, travel to and reflect at ABS2, and then travel around through the OC via reflection at mirrors m1 and m2, and return to ABS1. The signal photon may reflect at ABS1, travel to and reflect at ABS2, and travel a second time around through the OC via reflection at mirrors m1 and m2, and return to ABS1.

The signal photon may then reflect at ABS1, travel to and pass through ABS2, then travel to and reflect at mirror m3 and travel to ABS3. The photon may then reflect at ABS3 and travel to mirror m5.

Alternately, after making two cycles around through the OC, the signal photon may pass through ABS1, travel to and reflect at mirror m4 and travel ABS3. The photon may then pass through ABS3 and travel to mirror m5.

These two possible paths for the signal photon are equal in optical path length, so the signal photon arrives at mirror m5 with probability amplitude:

$$pa_1(m5,2) = -i[(t_1\ r_2^2\ r_1^2\ t_2\ r_3) - (t_1\ r_2^2\ r_1\ t_1\ t_3)]$$

If the signal photon arrives at mirror m5 with probability amplitude $pa_1(m5,2)$, then it arrives at mirror m5 after it would have arrived with probability amplitude $pa_1(m5,1)$ by a time equal to X.

The photon reflects at mirror m5 and travels to ABS4.

Initially, the signal photon may pass through ABS1, travel to and reflect at ABS2, and then travel around through the OC via reflection at mirrors m1 and m2, and return to ABS1. The signal photon may reflect at ABS1, travel to and reflect at ABS2, and travel a second time around through the OC via reflection at mirrors m1 and m2, and return to ABS1.

The signal photon may reflect at ABS1, travel to and pass through ABS2, then travel to and reflect at mirror m3 and travel to ABS3. The photon may then pass through ABS3 and travel to mirror m6.

Alternately, after making two cycles around through the OC, the signal photon may pass through ABS1, travel to and reflect at mirror m4 and travel ABS3. The photon may then reflect at ABS3 and travel to mirror m6.

These two possible paths for the signal photon are equal in optical path length, so the signal photon arrives at mirror m6 with probability amplitude:

$$pa_1(m6,2) = -[(t_1\ r_2^2\ r_1^2\ t_2\ t_3) + (t_1\ r_2^2\ r_1\ t_1\ r_3)]$$

If the signal photon arrives at mirror m6 with probability amplitude $pa_1(m6,2)$, then it arrives at mirror m6 after it would have arrived with probability amplitude $pa_1(m6,1)$ by a time equal to X.

The photon reflects at mirror m6 and travels to ABS4. Path lengths are set so that the signal photon component from mirror m5 and the component from mirror m6 arrive at ABS4 at the same time.

Since both components are of the same signal photon, one-photon interference occurs at ABS4. The probability amplitude incident on detector D3 is:

$$pa_1(D3,2) = +i[(t_1\ r_2^2\ r_1^2\ t_2\ r_3) - (t_1\ r_2^2\ r1\ t_1\ t_3) - (t_1\ r_2^2\ r_1^2\ t_2\ t_3) - (t_1\ r_2^2\ r1\ t_1\ r_3)]/[\sqrt{(2)}]$$

The probability amplitude incident on detector D2 is:

$$pa_1(D2,2) = +[(t_1\ r_2^2\ r_1^2\ t_2\ r_3) - (t_1\ r_2^2\ r1\ t_1\ t_3) + (t_1\ r_2^2\ r_1^2\ t_2\ t_3) + (t_1\ r_2^2\ r1\ t_1\ r_3)]/[\sqrt{(2)}]$$

With: $t_1(r_3+t_3) = (r_1t_2)(r_3-t_3)$ and $r_3>t_3$:

$$pa_1(D3,2) = 0$$

$$pa_1(D2,2) = +\{[((t_1\ r_1^2\ t_2\ r_2^2)(r_3+t_3))+((t_1^2\ r_1\ r_2^2)(r_3-t_3))]/[\sqrt{(2)}]\}$$

If the signal photon is incident on detector D2 with probability amplitude $pa_1(D2,2)$, then it is incident after it would have been incident on detector D2 with probability amplitude $pa_1(D2,1)$ by a time equal to X.

IV) This process may repeat with the signal photon making additional cycles around through the OC, until it is incident on detector D2 in the Transmitter. In general (for integer $N \geq 1$):

$pa_1(D3,N) = 0$

$pa_1(D2,N) =$

$+\{[((t_1 r_1 t_2 r_2)(r_3 + t_3)) + ((t_1^2 r_2)(r_3 - t_3))]/[\sqrt{(2)}]\}(r_1 r_2)^{(N-1)}$

V) If the signal photon of a down-converted pair travels from the Source to the Transmitter and is detected in either detector D2 as probability amplitude component $pa_1(D2,0)$ or in detector D3 as probability amplitude component $pa_1(D3,0)$, and the idler photon of the pair travels to the Receiver, passes through the short path through the MZ, and is detected in either detector D4 or D5, then the time between the detection of the signal photon in the Transmitter and the idler photon in the Receiver is equal to ∂. The time ∂ is somewhat less than the time τ. Note that $\partial >> X$.

If the time difference between the detection of a signal photon in the Transmitter in detector D3, and the detection in the Receiver in detector D4 or detector D5 of the idler photon of the down-converted pair is equal to $(\partial+X)$, then there is no ambiguity as to which paths the photons travelled.

The signal photon reached detector D3 as component $pa_1(D3,0)$ and the idler photon travelled via the long path through the MZ to detector D4 or detector D5 in the Receiver.

Because there is no ambiguity in this case, non-local, two-photon interference does not occur. The probability amplitudes and probabilities in this case are:

$pa_1[D3,D4,(\partial+X)] = [pa(D3,0)][+ir_5r_6]$

$= \{+i[(r_1(r_3+t_3)) + ((t_1t_2)(r_3-t_3))]/[\sqrt{(2)}]\}[+i/2]$

$= -[(r_1(r_3+t_3)) + ((t_1t_2)(r_3-t_3))]/[2\sqrt{(2)}]$

$P_1[D3,D4,(\partial+X)] = |pa_1[D3,D4,(\partial+X)]|^2$

$= |[r_1^2(r_3+t_3)^2] + [t_1^2t_2^2(r_3-t_3)^2] + [(2r_1t_1t_2)(r_3^2-t_3^2)]|/8$

$$pa_1[D3,D5,(\partial+X)] = [pa(D3,0)][+r_5t_6]$$

$$= \{+i[(r_1(r_3+t_3)) + ((t_1t_2)(r_3-t_3))]/[\sqrt{(2)}]\}[+1/2]$$

$$= +i[(r_1(r_3+t_3)) + ((t_1t_2)(r_3-t_3))]/[2\sqrt{(2)}]$$

$$P_1[D3,D5,(\partial+X)] = \left|pa_1[D3,D5,(\partial+X)]\right|^2$$

$$= \left|[r_1^2(r_3+t_3)^2] + [t_1^2t_2^2(r_3-t_3)^2] + [(2r_1t_1t_2)(r_3^2-t_3^2)]\right|/8$$

Note that: $P_1[D3,D4,(\partial+X)] = P_1[D3,D5,(\partial+X)]$

If the time difference between the detection of a signal photon in the Transmitter in detector D3, and the detection in the Receiver in detector D4 or detector D5 of the idler photon of the down-converted pair is equal to ∂, then there is no ambiguity as to which paths the photons travelled.

The signal photon reached detector D3 as component $pa_1(D3,0)$ and the idler photon travelled via the short path through the MZ to detector D4 or detector D5 in the Receiver.

Because there is no ambiguity in this case, non-local, two-photon interference does not occur. The probability amplitudes and probabilities in this case are:

$$pa_1[D3,D4,(\partial)] = [pa(D3,0)][+it_5t_6]$$

$$= \{+i[(r_1(r_3+t_3)) + ((t_1t_2)(r_3-t_3))]/[\sqrt{(2)}]\}[+i/2]$$

$$= -[(r_1(r_3+t_3)) + ((t_1t_2)(r_3-t_3))]/[2\sqrt{(2)}]$$

$$P_1[D3,D4,(\partial)] = \left|pa_1[D3,D4,(\partial)]\right|^2$$

$$= \left|[r_1^2(r_3+t_3)^2] + [t_1^2t_2^2(r_3-t_3)^2] + [(2r_1t_1t_2)(r_3^2-t_3^2)]\right|/8$$

$$pa_1[D3,D5,(\partial)] = [pa(D3,0)][-t_5r_6]$$

$$= \{+i[(r_1(r_3+t_3)) + ((t_1t_2)(r_3-t_3))]/[\sqrt{(2)}]\}[-1/2]$$

$$= -i[(r_1(r_3+t_3)) + ((t_1t_2)(r_3-t_3))]/[2\sqrt{(2)}]$$

$$P_1[D3,D5,(\partial)] = \left|pa_1[D3,D5,(\partial)]\right|^2$$

$$= \left|[r_1^2(r_3+t_3)^2] + [t_1^2t_2^2(r_3-t_3)^2] + [(2r_1t_1t_2)(r_3^2-t_3^2)]\right|/8$$

Note that: $P_1[D3,D4,(\partial)] = P_1[D3,D5,(\partial)]$

VI) If the time difference between the detection of a signal photon in the Transmitter in detector D2, and the detection in the Receiver in detector D4 or detector D5 of the idler photon of the down-converted pair is equal to $(\partial+X)$, then there is no ambiguity as to which paths the photons travelled.

The signal photon reached detector D2 as component $pa_1(D2,0)$ and the idler photon travelled via the long path through the MZ to detector D4 or detector D5 in the Receiver.

Because there is no ambiguity in this case, non-local, two-photon interference does not occur. The probability amplitudes and probabilities in this case are:

$$pa_1[D2,D4,(\partial+X)] = [pa(D2,0)][+ir_5r_6]$$

$$= \{+[((t_1t_2)(r_3+t_3)) - (r_1(r_3-t_3))]/[\surd(2)]\}[+i/2]$$

$$= +i[((t_1t_2)(r_3+t_3)) - (r_1(r_3-t_3))]/[2\surd(2)]$$

$$P_1[D2,D4,(\partial+X)] = |pa_1[D2,D4,(\partial+X)]|^2$$

$$= |[r_1^2(r_3+t_3)^2] + [t_1^2t_2^2(r_3-t_3)^2] + [(2r_1t_1t_2)(r_3^2-t_3^2)]|/8$$

$$pa_1[D2,D5,(\partial+X)] = [pa(D2,0)][+r_5t_6]$$

$$= \{+[((t_1\ t_2)(r_3+t_3)) - (r_1(r_3-t_3))]/[\surd(2)]\}[+1/2]$$

$$= +[((t_1t_2)(r_3+t_3)) - (r_1(r_3-t_3))]/[2\surd(2)]$$

$$P_1[D2,D5,(\partial+X)] = |pa_1[D2,D5,(\partial+X)]|^2$$

$$= |[r_1^2(r_3+t_3)^2] + [t_1^2t_2^2(r_3-t_3)^2] + [(2r_1t_1t_2)(r_3^2-t_3^2)]|/8$$

Note that: $P_1[D2,D4,(\partial+X)] = P_1[D2,D5,(\partial+X)]$

If the time difference between the detection of a signal photon in the Transmitter in detector D2, and the detection in the Receiver in detector D4 of the idler photon of the down-converted pair is equal to ∂, then there is an ambiguity as to which paths the photons travelled.

The signal photon may have reached detector D2 as component $pa_1(D2,0)$ and the idler photon may have travelled via the short path through the MZ to detector D4 in the Receiver.

Alternately, the signal photon may have reached detector D2 as component $pa_1(D2,1)$ and the idler photon may have travelled via the long path through the MZ to detector D4 in the Receiver.

Because of this ambiguity, non-local, two-photon interference occurs [1]. The probability amplitudes of the two possibilities must be combined. The probability amplitude and probability in this case are:

$$pa_1[D2,D4,(\partial)] = [pa(D2,0)][it_5t_6] + [pa(D2,1)][ir_5r_6]$$

$$= +i[((t_1t_2)(1+r_1r_2)(r_3+t_3))+((t_1^2r_2-r_1)(r_3-t_3))]/[2\surd(2)]$$

$$P_1[D2,D4,(\partial)] = \left|pa_1[D2,D4,(\partial)]\right|^2$$

$$= \left|[((t_1t_2)^2(1+r_1r_2)^2(r_3+t_3)^2)+((t_1^2r_2-r_1)^2(r_3-t_3)^2)\right.$$

$$\left. + (2(t_1t_2)(1+r_1r_2)(t_1^2r_2-r_1)(r_3^2-t_3^2))]/8\right|$$

If the time difference between the detection of a signal photon in the Transmitter in detector D2, and the detection in the Receiver in detector D5 of the idler photon of the down-converted pair is equal to ∂, then there is an ambiguity as to which paths the photons travelled.

The signal photon may have reached detector D2 as component $pa_1(D2,0)$ and the idler photon may have travelled via the short path through the MZ to detector D5 in the Receiver.

Alternately, the signal photon may have reached detector D2 as component $pa_1(D2,1)$ and the idler photon may have travelled via the long path through the MZ to detector D5 in the Receiver.

Because of this ambiguity, non-local, two-photon interference occurs [1]. The probability amplitudes of the two possibilities must be combined. The probability amplitude and probability in this case are:

$$pa_1[D2,D5,(\partial)] = [pa(D2,0)][-t_5r_6] + [pa(D2,1)][+r_5t_6]$$

$$= -[((t_1t_2)(1-r_1r_2)(r_3+t_3))-((t_1^2r_2+r_1)(r_3-t_3))]/[2\surd(2)]$$

$$P_1[D2,D5,(\partial)] = \left|pa_1[D2,D5,(\partial)]\right|^2$$

$$= \left|[((t_1t_2)^2(1-r_1r_2)^2(r_3+t_3)^2)+((t_1^2r_2+r_1)^2(r_3-t_3)^2)\right.$$

$$\left. - (2(t_1t_2)(1-r_1r_2)(t_1^2r_2+r_1)(r_3^2-t_3^2))]/8\right|$$

Note that: $P_1[D2,D4,(\partial)] > P_1[D2,D5,(\partial)]$

If the time difference between the detection of a signal photon in the Transmitter in detector D2, and the detection in the Receiver in detector D4 of the idler photon of the down-converted pair is equal to $(\partial-X)$, then there is an ambiguity as to which paths the photons travelled.

The signal photon may have reached detector D2 as component $pa_1(D2,1)$ and the idler photon may have travelled via the short path through the MZ to detector D4 in the Receiver.

Alternately, the signal photon may have reached detector D2 as component $pa_1(D2,2)$ and the idler photon may have travelled via the long path through the MZ to detector D4 in the Receiver.

Because of this ambiguity, non-local, two-photon interference occurs [1]. The probability amplitudes of the two possibilities must be combined. The probability amplitude and probability in this case are:

$$pa_1[D2,D4,(\partial-X)] = [pa(D2,1)][it_5t_6] + [pa(D2,2)][ir_5r_6]$$

$$= +i[((t_1r_1t_2r_2)(1+r_1r_2)(r_3+t_3))+((t_1^2r_2)(1+r_1r_2)(r_3-t_3))]/[2\surd(2)]$$

$$P_1[D2,D4,(\partial-X)] = \left|pa_1[D2,D4,(\partial-X)]\right|^2$$

$$= \left|[((t_1r_1t_2r_2)^2(1+r_1r_2)^2(r_3+t_3)^2)+((t_1^2r_2)^2(1+r_1r_2)^2(r_3-t_3)^2) + (2(t_1r_1t_2r_2)(1+r_1r_2)^2(t_1^2r_2)(r_3^2-t_3^2))]/8\right|$$

$$= \left|\{[(1+r_1r_2)^2][((t_1r_1t_2r_2)^2(r_3+t_3)^2)+((t_1^2r_2)^2(r_3-t_3)^2) + (2(t_1r_1t_2r_2)(t_1^2r_2)(r_3^2-t_3^2))]\}/8\right|$$

If the time difference between the detection of a signal photon in the Transmitter in detector D2, and the detection in the Receiver in detector D5 of the idler photon of the down-converted pair is equal to $(\partial$-X), then there is an ambiguity as to which paths the photons travelled.

The signal photon may have reached detector D2 as component $pa_1(D2,1)$ and the idler photon may have travelled via the short path through the MZ to detector D5 in the Receiver.

Alternately, the signal photon may have reached detector D2 as component $pa_1(D2,2)$ and the idler photon may have travelled via the long path through the MZ to detector D5 in the Receiver.

Because of this ambiguity, non-local, two-photon interference occurs [1]. The probability amplitudes of the two possibilities must be combined. The probability amplitude and probability in this case are:

$$pa_1[D2,D5,(\partial-X)] = [pa(D2,1)][-t_5r_6] + [pa(D2,2)][+r_5t_6]$$

$$= -[((t_1r_1t_2r_2)(1-r_1r_2)(r_3+t_3))+((t_1^2r_2)(1-r_1r_2)(r_3-t_3))]/[2\surd(2)]$$

$$P_1[D2,D5,(\partial-X)] = \left|pa_1[D2,D5,(\partial-X)]\right|^2$$

$$= \left|[((t_1r_1t_2r_2)^2(1-r_1r_2)^2(r_3+t_3)^2)+((t_1^2r_2)^2(1-r_1r_2)^2(r_3-t_3)^2) + (2(t_1r_1t_2r_2)(1-r_1r_2)^2(t_1^2r_2)(r_3^2-t_3^2))]/8\right|$$

$$= \left|\{[(1-r_1r_2)^2][((t_1r_1t_2r_2)^2(r_3+t_3)^2)+((t_1^2r_2)^2(r_3-t_3)^2) + (2(t_1r_1t_2r_2)(t_1^2r_2)(r_3^2-t_3^2))]\}/8\right|$$

Note that: $P_1[D2,D4,(\partial-X)] > P_1[D2,D5,(\partial-X)]$

If the time difference between the detection of a signal photon in the Transmitter in detector D2, and the detection in the Receiver in detector D4 of the idler photon of the down-converted pair is equal to $(\partial-2X)$, then there is an ambiguity as to which paths the photons travelled.

The signal photon may have reached detector D2 as component $pa_1(D2,2)$ and the idler photon may have travelled via the short path through the MZ to detector D4 in the Receiver.

Alternately, the signal photon may have reached detector D2 as component $pa_1(D2,3)$ and the idler photon may have travelled via the long path through the MZ to detector D4 in the Receiver.

Because of this ambiguity, non-local, two-photon interference occurs [1]. The probability amplitudes of the two possibilities must be combined. The probability amplitude and probability in this case are:

$$pa_1[D2,D4,(\partial-2X)] = [pa(D2,2)][it_5t_6] + [pa(D2,3)][ir_5r_6]$$

$$= +i[((t_1r_1^2t_2r_2^2)(1+r_1r_2)(r_3+t_3))+((t_1^2r_1r_2^2)(1+r_1r_2)(r_3-t_3))]/[2\surd(2)]$$

$$P_1[D2,D4,(\partial-2X)] = \left|pa_1[D2,D4,(\partial-2X)]\right|^2$$

$$= \left|[((t_1r_1^2t_2r_2^2)^2(1+r_1r_2)^2(r_3+t_3)^2)+((t_1^2r_1r_2^2)^2(1+r_1r_2)^2(r_3-t_3)^2) + (2(t_1r_1^2t_2r_2^2)(1+r_1r_2)^2(t_1^2r_1r_2^2)(r_3^2-t_3^2))]/8\right|$$

$$= \left|\{[(1+r_1r_2)^2][((t_1r_1^2t_2r_2^2)^2(r_3+t_3)^2)+((t_1^2r_1r_2^2)^2(r_3-t_3)^2) + (2(t_1r_1^2t_2r_2^2)(t_1^2r_1r_2^2)(r_3^2-t_3^2))]\}/8\right|$$

If the time difference between the detection of a signal photon in the Transmitter in detector D2, and the detection in the Receiver in detector D5 of the idler photon of the down-converted pair is equal to $(\partial-2X)$, then there is an ambiguity as to which paths the photons travelled.

The signal photon may have reached detector D2 as component $pa_1(D2,2)$ and the idler photon may have travelled via the short path through the MZ to detector D5 in the Receiver.

Alternately, the signal photon may have reached detector D2 as component $pa_1(D2,3)$ and the idler photon may have travelled via the long path through the MZ to detector D5 in the Receiver.

Because of this ambiguity, non-local, two-photon interference occurs [1]. The probability amplitudes of the two possibilities must be combined. The probability amplitude and probability in this case are:

$$pa_1[D2,D5,(\partial-2X)] = [pa(D2,2)][-t_5r_6] + [pa(D2,3)][+r_5t_6]$$

$$= -[((t_1r_1^2t_2r_2^2)(1-r_1r_2)(r_3+t_3))+((t_1^2r_1r_2^2)(1-r_1r_2)(r_3-t_3))]/[2\sqrt{(2)}]$$

$$P_1[D2,D5,(\partial-2X)] = \left|pa_1[D2,D5,(\partial-2X)]\right|^2$$

$$= \Big|[((t_1r_1^2t_2r_2^2)^2(1-r_1r_2)^2(r_3+t_3)^2)+((t_1^2r_1r_2^2)^2(1-r_1r_2)^2(r_3-t_3)^2)$$
$$+ (2(t_1r_1^2t_2r_2^2)(1-r_1r_2)^2(t_1^2r_1r_2^2)(r_3^2-t_3^2))]/8\Big|$$

$$= \Big|\{[(1-r_1r_2)^2][((t_1r_1^2t_2r_2^2)^2(r_3+t_3)^2)+((t_1^2r_1r_2^2)^2(r_3-t_3)^2)$$
$$+ (2(t_1r_1^2t_2r_2^2)(t_1^2r_1r_2^2)(r_3^2-t_3^2))]\}/8\Big|$$

Note that: $P_1[D2,D4,(\partial-2X)] > P_1[D2,D5,(\partial-2X)]$

In general (for integer $N \geq 1$):

$$P_1[D2,D4,(\partial-NX)] = \Big|\{[(1+r_1r_2)^2(r_1r_2)^{(2(N-1))}]$$
$$[((t_1r_1t_2r_2)^2(r_3+t_3)^2)+((t_1^2r_2)^2(r_3-t_3)^2)$$
$$+ (2(t_1r_1t_2r_2)(t_1^2r_2)(r_3^2-t_3^2))]\}/8\Big|$$

$$P_1[D2,D5,(\partial-NX)] = \Big|\{[(1-r_1r_2)^2(r_1r_2)^{(2(N-1))}]$$
$$[((t_1r_1t_2r_2)^2(r_3+t_3)^2)+((t_1^2r_2)^2(r_3-t_3)^2)$$
$$+ (2(t_1r_1t_2r_2)(t_1^2r_2)(r_3^2-t_3^2))]\}/8\Big|$$

Note that: $P_1[D2,D4,(\partial-NX)] > P_1[D2,D5,(\partial-NX)]$

VII) The probabilities for the detection of idler photons in detectors D4 and D5 in the Receiver are (for integer $N \geq 1$):

$$P_1[D4] = P_1[D3,D4,(\partial+X)] + P_1[D3,D4,(\partial)] + P_1[D2,D4,(\partial+X)] + P_1[D2,D4,(\partial)] + \sum_N (P_1[D2,D4,(\partial-NX)])$$

$$P_1[D5] = P_1[D3,D5,(\partial+X)] + P_1[D3,D5,(\partial)] + P_1[D2,D5,(\partial+X)] + P_1[D2,D5,(\partial)] + \sum_N (P_1[D2,D5,(\partial-NX)])$$

Since: $P_1[D3,D4,(\partial+X)] = P_1[D3,D5,(\partial+X)]$,

$P_1[D3,D4,(\partial)] = P_1[D3,D5,(\partial)]$, $P_1[D2,D4,(\partial+X)] = P_1[D2,D5,(\partial+X)]$,

$P_1[D2,D4,(\partial)] > P_1[D2,D5,(\partial)]$, $P_1[D2,D4,(\partial-NX)] > P_1[D2,D5,(\partial-NX)]$

In the binary one case:

$P_1[D4] > P_1[D5]$

Note that every down-converted signal and idler photon pair communicates information from the Transmitter to the Receiver, rather than only one in every 10^6 pairs (as in a previous version of Delphi).

However, an integration time is required. The set integration time (I) required per bit must be of adequate duration to guarantee that a sufficient number of signal and idler photon pairs will be detected at the Transmitter and Receiver to ensure that the operator at the Receiver can make a statistically sound decision as to whether a binary one ($P_1[D4] > P_1[D5]$)or a binary zero ($P_0[D4] = P_0[D5]$) is being transmitted. Integration time I must also take into account all system losses.

5. Conclusion

The binary zero and binary one messages produce different detection probabilities at the Receiver. The operator at the Receiver notes whether the detections in detectors D4 and D5 correspond to a binary zero or a binary one message.

Communication may begin once signal photons from the Source reach the Transmitter and idler photons reach the Receiver. The transfer of information from the Transmitter to the Receiver is almost instantaneous (independent of distance), limited only by the required integration time per bit (I).

The time required to transmit one bit of information from the Transmitter to the Receiver is equal to I. The distance (D) associated with the integration time is:

$$D = c \cdot I$$

If the distance between the Transmitter and the Receiver is greater than D, then, using this system, the speed of transmission of information from Transmitter to Receiver will be faster than the speed of light.

Delphi 4A is a simple superluminal communication system.

In this paper, the variable designation "pa" is used, rather than "Ψ", to emphasize that the probability amplitude is a unitless complex number (only).

Probability amplitude is the square root of a probability. It is neither energy nor matter, but it controls the Universe. Its physical mechanism is still unknown. (By which of the four known forces of Nature does quantum entanglement "communicate"?)

References

[1] J. D. Franson, "Bell Inequality for Position and Time", Physical Review Letters 62, 2205 (1989).

[2] G. Weihs and A. Zeilinger, "Photon Statistics at Beam Splitters", Coherence and Statistics of Photons and Atoms, J. Perina (ed.), John Wiley & Sons, Inc. (2001).

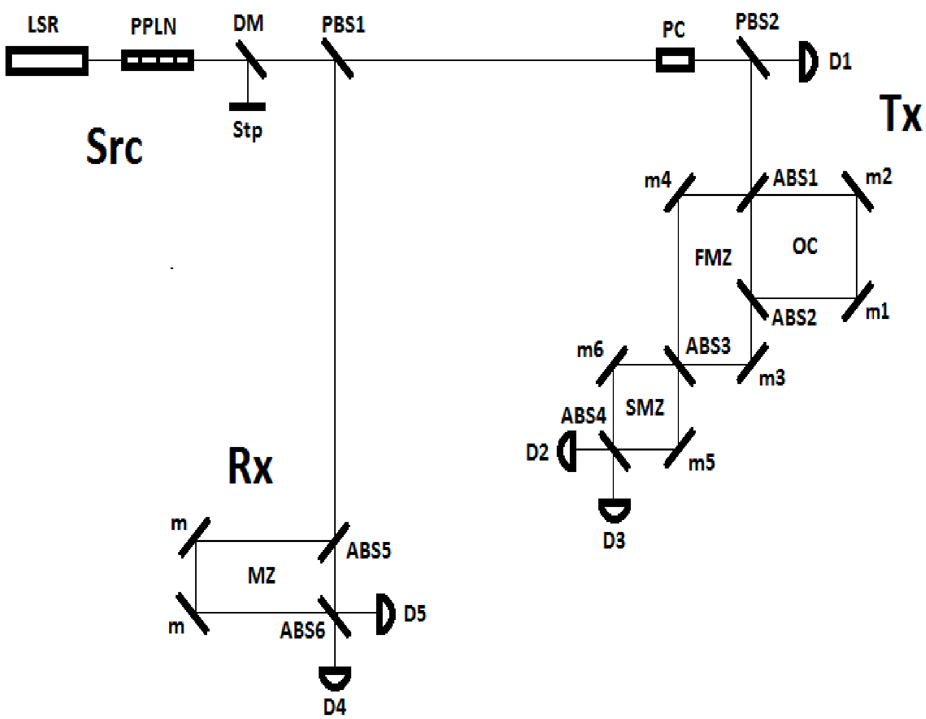

Figure 1: System Design