Reference: P-number assigned by Patent Department
Date: 2017-09-11
Submitted by:

Title of the invention

Give the invention a short describing title (slogan) that reflects what the invention is about. Avoid using more than 6 words.

Communication and error correction using ordering of polarised single-photons

Do you know of any publication/implementation dates and/or deadlines for this invention?
Please also clearly indicate this in your e-mail when submitting the Invention Disclosure (IvD).

☒ Yes	Please specify when:	January 15, 2023
	Reason for this publication:	Start of 2 master thesis projects
☐ No		

Planned publications (intermediate publications)

If the present application is filed in view of an upcoming publication, that is, if a disclosure of the invention to a third party such as a customer or a standardization body is expected, please indicate this and indicate the planned date for such a disclosure. Typically, contributions to standardization bodies, e.g. Change Requests, are considered as publications.

Please annex the planned publication to the Invention Disclosure. The planned publication document shall not be a substitute for the items in the present Invention Disclosure form. Hence, the annex will and should normally contain redundant material.

If the time for drafting an application is very short, Patent Development may decide to file a provisional application. In such a case, it is important that the exemplary solutions presented are reasonably complete and that the DETAILED DESCRIPTION OF EXAMPLES OF THE PROPOSED SOLUTION AND FIGURES are sufficiently detailed for being converted into a patent application in a short period of time.

The application should be filed before the planned publication.

How to write an Invention Disclosure (IvD)

Please fill in the invention disclosure template and submit to the Ericsson Patent Organization according to the instructions on the intranet.

This template only contains a short instruction summary for each paragraph. Please review the document Invention Disclosure Instructions for more detailed information on how to write an Invention Disclosure.

A completed invention disclosure should be classified as confidential and handled accordingly. Use encrypted e-mail.

1 TECHNICAL AREA / KEYWORDS

Please present the technical area (in a few key words) and when applicable indicate relevant protocol or data layer(s) that this invention relates to.

Information transmission, polarization, error correction

2 BACKGROUND

2.1 Technical background / Existing technology

*Briefly discuss/explain the technical background/context of the existing technical solutions related to your invention, but please **only disclose what is known to be prior art** in this section! Do **not** describe your solution here. This part is important and helps to understand **the technical basis** of your invention. List references in the References section below.*

If you have done any search of your own e.g. using the search tools available at http://internal.ericsson.com/employee-service/5356/search-tools-patent-and-scientific-information please only include the results that you consider to be most relevant.

A question raised in previous work [1, 2, 3, 4] is how much information could be carried by a single photon. Motivations for this include energy saving when available power is limited, such as in satellite applications.
In [5], it is shown that a single photon can be used for conveying more than 10 bits of information, by associating each photon with one of the pixels of a grid of detectors, i.e., associating it with one of 9072 spatial modes. Although this technique works well over short distances, it would not help much in a communication scenario over longer distances. In pulse position modulation (PPM), see [6], more than one bit can be transmitted per pulse over a single spatial mode, and thus this technique allows for message transmissions at a much lower total energy, utilising the fact that the “no pulse” state carries no energy.

[1] J. Pierce, “Optical channels: Practical limits with photon counting,” IEEE Transactions on Communications, vol. 26, no. 12, pp. 1819–1821, 1978.
[2] R. McEliece, “Practical codes for photon communication,” IEEE Transactions on Information Theory, vol. 27, no. 4, pp. 393–398, 1981.
[3] S. Butman, J. Katz, and J. Lesh, “Bandwidth limitations on noiseless optical channel capacity,” IEEE Transactions on Communications, vol. 30, no. 5, pp. 1262–1264, 1982.
[4] J. Lesh, “Capacity limit of the noiseless, energy-efficient optical ppm channel,” IEEE Transactions on Communications, vol. 31, no. 4, pp. 546–548, 1983.
[5] T. B. H. Tentrup, T. Hummel, T. A. W. Wolterink, R. Uppu, A. P. Mosk, and P. W. H. Pinkse, “Transmitting more than 10 bit with a single photon,” Optics Express, vol. 25, no. 3, p. 2826, 2017.
[6] Wikipedia contributors, “Pulse-position modulation — Wikipedia, the free encyclopedia.” https://en.wikipedia.org/wiki/Pulse-position_modulation, 2022. [Online; accessed2022 − 08 − 25].

2.2 Problems with existing solutions

Indicate one or more problems with the existing technology and why a solution is needed without disclosing your solution.

In this work, we address the lack of error-correction in PPM and devise a code that can correct both for lost pulses and for new pulses appearing in a block. The latter type of error can be due to reflections. To this end, we associate a single photon or a pulse with a variable integer number of time bins. Note that the advantages come at a cost, namely that the message will need more time for its transmission compared to traditional block coded communication protocols.

Note that the scheme presented uses single-photons, the same technique could in principle be used in any situation when a pulse can have extra degrees of freedom, e.g., in the form of polarisation.

Our scheme also bears some resemblance to the so called permutation codes, see e.g., work by Blake [7].

[7] I. F. Blake, G. Cohen, and M. Deza, "Coding with permutations," Information and Control, vol. 43, no. 1, pp. 1–19, 1979.

3 BRIEF SUMMARY OF THE PROPOSED SOLUTION / ABSTRACT

Explain in a few sentences HOW the problem above is solved by your solution without going into details. Include the main objectives. Describe the solution in general terms and as concisely as possible but still including the technical effect(s) achieved by the solution. Please remember that this is a brief description!

We propose a communication scheme with error correction for photon-starved scenarios. The scheme is inspired by to PPM [6] and permutation coding [7], but also exploit a polarisation degree of freedom, which allows for efficient correction of two common types of errors, loss and unwanted pulses (e.g., from reflections).

4 ADVANTAGES OF THE PROPOSED SOLUTION

Elaborate the advantages/technical benefits of your solution.

The main advantages of the proposed solution are that we can transmit information more reliably compared to [6] due to the special type of error correction adopted for an asymmetric channel, while still having the benefits of [6] in that communication can be used in photon-starved scenarios where considerably less than one photon per information bit is being sent. This is important in, e.g., satellite or other free-space telecommunication applications where low energy use is important.

5 DETAILED DESCRIPTION OF EXAMPLES OF THE PROPOSED SOLUTION AND FIGURES

*Please describe your solution as an exemplary **apparatus/node** that implements the solution and an exemplary **method** which describes the steps of the solution. If possible, describe your solution in terms of how it would be implemented in real-world solutions rather than in conceptual, abstract terms. Also, when applicable try to describe your solution from the perspective of a user terminal. In chapter 5.1 you are asked to exemplify in a cloud environment if applicable.*

To illustrate the description, please provide figures including:

- *a block diagram illustrating the novel apparatuses/nodes/circuits or the structures involved and*
- *a diagram, such as flow chart or signaling diagram, illustrating a method for implementing your solution.*

If you are aware of variants or alternatives of the solution beyond the basic apparatus/method described, you are encouraged to disclose such variants or alternatives, including such additional figures as these are appropriate to illustrate the alternatives of your solution. Also, when applicable try to include any use case related to the networked society/Internet of Things such as automotive and eHealth applications.

The figures in patent applications need to be in black and white, so please provide the figures in black and white in this document or as a separate file. If possible provide the figures in a format editable in Word, PowerPoint or Visio. If you use CAD software for the drawings, please provide a PDF as well.

If you provide the figures as a separate file, please number the figures and refer to those numbers in the text.

5.1 Formal recipe

First we define a block as an integral number of time bins (or other encoding resources that are orthogonal, i.e., that can be perfectly discriminated).

We then form a super block of n smaller blocks, whose lengths exhaust the first n integers of the sequense (1, 2, 4, 7, 12, 20, 29, 38, 52,…). This sequense has the property that pairwise sums of distinct elements from the sequense are all distinct. It was first described by Hoey, see [8].

The super block can be arranged in n! ways since each block length occurs exactly once in a super block. The conveyed information in such a block is upper bounded by log_2(n!). Note that this results in more than 1 bit of information per photon when n>3, i.e., when log_2(n!)/n > 1.

For each of the sub blocks, the first time bin contains a photon with one out of two orthogonal polarisations, e.g. horizontal (H) or vertical (V) linear polarisation. In the remaining text we will use a single photon, however, in principle the scheme could also be implemented with any polarised light pulse.

Any given block i is tagged with a "H" state if the next block i+1 is longer than block i, and with a "V" if the next block is shorter. For the last block i=n, it is tagged with an "H" ("V") if the first block i=1 is longer(shorter).

Example: Consider the case with three blocks of length 1, 2 and 4. They can be ordered in 3!=6 ways (124,142,214,241,412,421) and therefore transmit log_2(6) ~ 2.58 bits of information per super block. If the super block codeword 214 is sent, the quantum states V0 H V000 will be transmitted (the string indicates how the symbols are ordered in the time bins, starting with the first bin and finishing with the last).

5.2 Error correction capabilities

We will now demonstrate how errors can be identified and corrected using some simple rules, i.e., the error correction can take place without relying on tables. The suggested encoding can protect the super block from both loss and addition of a photon, as well as correct some types of multi-errors. Errors that can not be corrected at the receiver, can with high probability be detected, so that the information can be re-sent.

5.2.1 Loss of a photon

When a photon is lost, a block with length e, not in the list of allowed lengths, will be present and signal an error. We will need the polarisation to decide how to proceed.

Example: suppose we start with (1,2,4,7,12):

After a loss, we could get the sequences (3,4,7,12), (1,6,7,12),(1,2,11,12),(1,2,4,19). We could also lose the first photon, but this case is easy to correct since the start time of each super block is assumed to be known.

In each of these configurations, there is exactly one block with a disallowed length. If this block is initialised with a "H", we know that it is composed of two lengths, the first one smaller than the second. E.g., if the super block is (1,2,11,12), we know that the block of length 11 must be composed of (4,7) and not (7,4).

5.2.2 Addition of a photon

Suppose (1,2,4,7,12) was transmitted and an additional photon appears inside the "7" block.

The receiver would get one of (1,2,4,1,6,12), (1,2,4,2,5,12), (1,2,4,3,4,12), (1,2,4,4,3,12), (1,2,4,5,2,12), (1,2,4,6,1,12).

In this case, the receiver would see more blocks than expected, and one disallowed block length would indicate the position of the error. Next to the illegal length block will be a block whose length already appears once in the sequence. Thus, the error can be corrected by identifying this block and merge the two blocks. In one case, the situation is symmetric, i.e., for (1,2,4,3,4,12) and it is not immediately clear which block to merge with the illegal length block. But also in this case the error can be corrected using the polarisation information.

5.2.3 Some types of multi-errors can be corrected

Consider the situation where multiple non-adjacent photons were lost. For this purpose, we use the super block (1,2,4,7) as an example.

The super block would be encoded as HH0H000V000000.

Suppose that after transmission, the receiver gets $(3,11)=$ H00H0000000000. The receiver can conclude that likely 2 loss errors occurred (it could also be that 3 loss errors and one photon addition error occurred, but with a much lower probability). The 3 block can be corrected, since the initial photon is H, meaning that (2,1) is ruled out and therefore 3 →(1,2) is the correct mapping.

After correcting the 3 block, the 11 block can be corrected in the same manner.

5.2.4 Most uncorrectable errors can be detected

The code can not correct for 2 or more adjacent loss errors and some other multi-errors. However, most errors can be detected, since the agreed protocol states that a fixed number n of distinct block lengths should be present. With low probability, there could be errors stemming from a combination of addition and deletion, that could not be detected.

6 EXTENSION FOR STRONGER PULSES

When a general polarized pulse is considered (and not a single photon), one can distinguish between more polarization states than 2 (i.e., “H” and “V”). This means that one can extend the error correction so that it can handle the case of 2 adjacent loss errors. Since in this case, we can have, e.g., (1,2,4,7,12)→(1,13,12). The polarization information will in this case need 6 distinguishable symbols, call them a,b,c,d,e,f, to account for each of the 3!=6 orderings a=(2,4,7), b=(2,7,4), c=(4,2,7), d=(4,7,2), e=(7,2,4), f=(7,4,2), which will enable the correction of two adjacent loss errors. Thus, the sequence (1,2,4,7,12) would be encoded as “aa0a000d000000e00000000000”.

[8] Hoey, Dan, Sequense a010672 in the on-line encyclopedia of integer sequences. published electronically at https://oeis.org, 2016.

FIGURE(S) – STRUCTURE / NODE LEVEL ARCHITECTURE / PLATFORMS

*Please provide a **block diagram** illustrating the solution in detail.*

Insert figure here.

Click here to enter text describing the figure in detail.

FIGURE(S) - FUNCTIONS

*Please provide **flowcharts** and / or **handshake diagrams** illustrating the solution in detail (not needed if it is a pure hardware solution).*

If the exemplary solutions re-use existing signaling, please indicate new signals / features by way of a graphical emphasis / other indications in text and figures.

For clarity it may be beneficial to provide separate diagrams for various modes of operation rather than presenting overly many variants in one combined diagram. The same applies to the description; try to describe embodiments separately, start with the essential embodiment, continue with other variants explaining the differences.

Insert figure here.

Click here to enter text describing the figure in detail.

ADDITIONAL FIGURES

Please provide additional flowcharts/block diagrams/circuit diagrams/signaling diagrams/drawings as required for fully illustrating the solution(s).

Insert figure here.

Click here to enter text describing the figure in detail.

For additional clarification and emphasis of technical effects, a comparison to an internal reference implementation (e.g. an internally known solution or fictitious solution) may optionally be provided. This may be appropriate if the invention is a further development of an Ericsson solution that is not publicly available.

6.1 CLOUD IMPLEMENTATION

Many inventions can be implemented in a distributed manner across several nodes in a network. If that is the case for this invention, in order to get the best possible protection, it is important to note which steps and/or functions involved that may be executed in separate nodes and/or be subject to virtualization.

If applicable, please provide additional flowcharts/block diagrams/circuit diagrams/signaling diagrams/drawings as required for fully illustrating such an implementation.

CLOUD FIGURE(S)

Insert figure here.

Click here to enter text describing the figure in detail.

7 CORE ESSENCE OF THE SOLUTION

Please identify the essence or key features of your solution that brings about the desired technical effects or that solve a problem defined above, and help us determine what could be claimed in a patent application.

Please shortly describe what you consider to be important, new and involve an inventive step compared to the prior art, and thus ***what should be the focus of a patent application.***

We show that by utilizing the characteristics of two common error types; loss and false pulses (that could be e.g., due to cross-talk), an error correction code can be constructed that uses very little energy per pulse (much less than one photon per bit), but at the expense of a lower information rate (measured in bits per second). Previous similar inventions, like PPM, suffer from a lack of error control.

8 ABBREVIATIONS

Explain all abbreviations and acronyms used in the document.

Abbreviation	Explanation
PPM	pulse position modulation

9 REFERENCES

List only the most relevant and closely related references *you refer to in the disclosure, e.g. those mentioned in the Background section. If possible, please state where in the reference the relevant passage is located. You must keep a copy of all references. The references (preferably in electronic format) should be submitted to the Patent Department when submitting the Invention Disclosure. For textbooks and e.g. standard specifications you should submit copies of the relevant pages only.*

References List

Please list the references below with e.g. title, author, where and when it has been published, relevant chapters/ pages, ISBN, P-number if applicable etc. Please number enclosed references accordingly. If a standard document is referred to, indicate number, version and date (Usually the latest version). If particular sections / figures are relevant for understanding the invention do also refer to such.

[7] I. F. Blake, G. Cohen, and M. Deza, "Coding with permutations," Information and Control, vol. 43, no. 1, pp. 1–19, 1979.

10 INVENTION INFORMATION

Please note that answering the questions below (to your best knowledge) is MANDATORY.
This information helps the patent department to handle your invention in the best and most time efficient way.

10.1 Inventor information

Please underline a contact person. If no one is indicated the first inventor on the list will be contacted.

Inventor Name	**Corp. ID (SIGNUM)**	**Company, business org. and site** (e.g. Ericsson, BNET, Kista, SE)	**Share (%)**	**Nationality**	**Inventor's country of residence when writing the IvD**	**Country invention was made in**
Jonas Almlöf	Ejnmloa	Ericsson Research	35%	Swedish	Sweden	Sweden
Richard Schatz		Royal Institute of Technology (KTH)	25%	Swedish	Sweden	Sweden
Gemma Vall-llosera	egemval	Ericsson	10%	Swedish	Sweden	Sweden
Thomas Lettner		Royal Institute of Technology (KTH)	20%	Austrian	Sweden	Sweden
Valery Zwiller		Royal Institute of Technology (KTH)	10%	French	Sweden	Sweden

10.2 Invention origin

Is the invention directly related to your work?	☒Yes ☐No ☐Don't know
Do you know of any closely related Ericsson inventions? *Please state P-number(s) or Patent number(s) if known.*	☒Yes: P81444 "Error correction codes for single- photons in a dissipative channel" ☐No
When was your invention first documented/described?	June 1, 2022
When was the idea first reduced to practice? *(i.e. tested/simulated/verified/…)*	Click here to enter a date.

10.3 Ericsson expert(s) in this field

Name a technical expert(s): *Provide both name and Ericsson signum.*	Mattias Andersson W (enqrrvg)

Name a business expert(s) or product manager(s): *Provide both name and Ericsson signum.*	Gaspar Wosa (egaswos)

10.4 Project origin

Has this invention been created within a project?

☒ Yes ☐ No ☐ Don't know
If Yes; please answer ALL questions below:

Project name:	Single-photon communication and error correction, Vinnova, grant no.
Project manager:	Jonas Almlöf
Is this project:	☐ Internal ☒ Co-operation with external party: Royal Institute of Technology, Stockolm

10.5 ER Program origin

Has this invention been created within an Ericsson Research Program?

☒ Yes ☐ No ☐ Don't know
If Yes; please answer ALL questions below:

Program name:	Quantum program
Program manager:	Rana Pradap Sircar (eransir)

10.6 Will this invention be incorporated into an existing/future product?

☐ Yes ☐ No ☒ Don't know
If Yes; please answer ALL questions below:

Name of the product:	Click here to enter text.
Brief description of the product:	Click here to enter text.
Name the supplier/manufacturer if not Ericsson:	Click here to enter text. ☐ Don't know
Potential customers or markets:	Click here to enter text.
When will this product be released outside Ericsson?	Click here to enter a date if known.

10.7 Could this invention become <u>included</u> in any standard?

☐ Yes ☐ No ☒ Don't know
If Yes; please answer ALL questions below:

Please state the complete name of the standard, including release (e.g. "3GPP TS 36.331"):	Click here to enter text.
Do implementation of some aspects of this invention require any changes/additions to any standard(s)? Which changes?	Click here to enter text.
Can some aspects of the invention be implemented without any changes/additions to any standard(s)?	Click here to enter text.

Please state the Ericsson Standardization Team handling this standard.	Click here to enter text.
Please state the names of the related standardization study/work item, feature team, or other group related to this technology:	Click here to enter text.
Will Ericsson submit a standard contribution/proposal for this invention?	☒ Yes ☐ No ☒ Don't know *If Yes please state submission document number and version: Click here to enter text.* *Please provide a copy as soon as possible*

10.8 Could this invention be related to <u>implementation</u> in a node/equipment compatible with a standard?

☐ Yes ☐ No ☒ Don't know

If Yes; please answer ALL questions below:

Name of the related standard(s)*:*	Click here to enter text.
Type of the related node(s)/equipment(s): (e.g. UE, eNB, access point…)	Click here to enter text.
If the node/equipment consists of several parts, which part(s)? (e.g. baseband, radio ASIC, antenna…)?	Click here to enter text.

10.9 Open source relationship

Does the invention pertain or relate to any open-source interface or protocol or work within any virtualization or software defined networking (SDN) consortia, including, but not limited to: *Openstack, OpenFlow (Open Networking Foundation), OpenDaylight, CableLabs, TM Forum, ETSI NFV*? Or do you intend to include your invention into source code which is to be submitted to open source, or include code which is available as open source?

☐ Yes ☐ No ☐ Not Applicable ☒ Don't know

If yes, please indicate which open source interface, protocol or consortia:

Click here to enter text.

10.10 Public funded projects and/or projects with project partners

Is the invention an IPR result of the work in e.g. any EU project, a European Framework Program, BMBF funded or other governmental relation such as for example:

- Horizon 2020
- FP7
- Celtic-Plus
- EIT ICT Labs
- EIT Innoenergy

☐ Yes ☒ No ☐ Don't know

If Yes please specify the name of the project and the acronym(s) of the project:

Click here to enter text.

10.11 Strategic importance of the solution

Mark if this technical area/problem is:

☒ Future strategic area
☒ Strategic area
☒ Improvement on existing solution
☐ "Legacy" (the market is going away from this solution)
☐ Don't know

We believe that all industrial randomness generators will be based on this patent in the future.

10.12 Detection of infringement

How easy is it to detect infringement of this solution?

☐ Easy to detect (e.g. reading documentation or ocular inspection)
☒ Possible but requires extra effort (e.g. measuring output)
☐ Difficult to detect (e.g. reverse engineering)
☐ Don't know

Click here to enter text.

10.13 Energy improvements

Energy improvements are very valuable for Ericsson, our customers and the society. These energy improvements can be captured in design or in operation.

Could the present invention result in energy improvements?

☒ Yes ☐ No ☐ Don't know

Please specify at what level the energy improvement can be calculated/estimated for the invention.

☐ Node equipment
☒ Network level
☒ Society (i.e. even if the energy improvement is small, the accumulated improvement on a global level is substantial)

11 SUGGESTION FOR PERSONS HANDLING THIS INVENTION

Please note that it is OPTIONAL to fill in the fields below. If you have previously submitted an Invention Disclosure within this technical field, you may suggest a person/persons you think would be suited to handle this one as well.

This information helps the patent department to handle your invention in the best and most time efficient way. Please suggest one or several alternative names.

Ericsson patent engineer(s):	Sri Janani Rengarajan <sri.janani.rengarajan@ericsson.com>
External patent attorney(s):	Alastair Lowe at Haseltine Lake Kempner LLP