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DESCRIPTION

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**Robust Method and Apparatus Enabling Multi-Mode Wireless
Optical Communication****TECHNICAL FIELD**

10 The present invention relates to multi-mode wireless optical communication systems and the communication and/or coexistence of communication between different kinds of devices, operating in different modes, within such communication systems.

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BACKGROUND OF THE INVENTION

With the rapidly increasing number of workstations and personal computers (e.g. desktop or handheld ones) in all areas of business, administration, fabrication etc., there is also an increasing demand for flexible and simple
20 interconnection of these systems. There is a similar need as far as the hook-up and interconnection of peripheral devices, such as keyboards, computer mice, printers, plotters, fax machines, scanners, displays, modems, and so forth, is concerned. The use of electrical interconnects becomes a problem with increasing number of systems communicating with
25 each other, and in many cases in which the location of systems, or the configuration of subsystems, must be changed frequently. It is therefore desirable to gain flexibility by eliminating electrical interconnects for such systems and using wireless communication instead.

30 The use of optical signals for wireless transfer of digital data between systems and devices has received increased interest during recent years and has lead to applications in commercial products. One example is the optical remote control of electronic consumer devices. Another example is

1 the communication between information systems in an office environment. In
an optical communication system digital data to be transferred between a
transmitting system and a receiving system are transformed into modulated
optical signals which are radiated by a light source - in particular an
5 Infrared (IR) light source - of the transmitting system and are received,
converted to electrical signals and then into digital data by the receiving
system. The optical signals might directly propagate to the optical receiver
of the receiving system or they might indirectly reach the receivers after
changes of the direction of propagation due to processes like reflections or
10 scattering at surfaces. Today, the former case is realized in portable
computers and peripheral devices where the data transfer takes place
between an optical transmitter and a receiver which are close together at a
distance on the scale of 1-3m and properly aligned. The latter case is
typical for applications in an office environment in which undisturbed direct
15 transmission of optical signals between transmitters and receivers several
meters away from each other is impractical or even impossible due to
unavoidable perturbations of the direct path. One known approach to
achieve a high degree of flexibility is to radiate optical signals from the
transmitting system to the ceiling or walls of an office where they are
20 reflected or diffusely scattered. Thus, the radiation is distributed over a
certain zone in the surroundings of the transmitter. The distribution of the
light signals spreading from the ceiling depends on many details which are
characteristic for the particular environment under consideration. However,
essential in this context is mainly that the transmission range, i. e. the
25 distance between transmitting system and receiving system, is limited to
some final value, hereafter called the transmission range, since the energy
flux of the transmitted radiation decreases with increasing distance of
propagation and the receiver sensitivity is limited due to a minimum
signal-to-noise ratio. Typical known systems, operating at levels of optical
30 power which are limited by the performance of the light sources and safety
requirements for light exposure, have demonstrated transmission ranges of
several meters for data rates of 1 Mbps.

1 The latter example illustrates basic features of wireless optical
communication and indicates fields of applications where it is favorably
applied in contrast to another competitive method of wireless
communication, the radio frequency (RF) transmission. Wireless optical
5 communication allows data transmission which is short range, whereas RF
transmission is potentially long range. Furthermore, optical wireless
communication in an office environment is localized since typical
boundaries of an office such as walls and ceilings are not transparent for
light but generally for RF waves. That is why possible interferences between
10 different communication systems are easier to control and a simpler way for
achieving data security is possible for a wireless communication system
which is based on optical radiation rather than RF transmission. RF
transmission is even restricted by communications regulations and licenses
whereas optical wireless communication systems are not.

15
Crucial performance parameters of a wireless optical communication system
are the achievable data rate and the distance between the systems
exchanging data. In an office environment, it can be necessary to
communicate data over distances exceeding the transmission range of a
20 single optical transmitter. However, the transmission range of a single
optical transmitter can be extended within the concept of wireless
communication, for example by introducing optical repeaters. One example
of such an extended system has been proposed in US patent 4 402 090
entitled "Communication System in which Data are Transferred Between
25 Terminal Stations and Satellite Stations by Infrared Systems". In this patent,
a system is described which provides a plurality of satellite stations, i. e.
stations usually fixed at the ceiling of a large room. Terminals can optically
interact with satellites within their transmission range, and data can be
distributed via intersatellite communication thus enabling the distribution of
30 data over distances beyond the transmission range of a single transmitter.

When designing a wireless optical communication system, one has to be
aware of unavoidable ambient light, such as daylight or light from lamps,

1 which always reaches the optical detectors, unless the system is restricted
for the use in a completely dark environment. The IR energy in ambient
light (fluorescent and incandescent lamps, sun light) can lead to dominant
noise in the optical receiver. Thus, ambient light influences the
5 signal-to-noise ratio of the receiver and, therefore, affects the transmission
range. Further details on the effect of ambient light are outlined in the
pending PCT patent applications PCT/EP 94/01196, published on 26 October
1995 (Publication No. WO 95/28777). The appearance of ambient light is
mostly statistical and often difficult to control and its intensity can drastically
10 change, as it is apparent for lamps being switched on/off, or sunlight. A
further realistic effect which statistically affects the signal-to-noise ratio and
thus the transmission range is the occurrence of optical path obstructions
influencing the receiver signal. In an office environment, for example,
moving users can change the strength of the transmitted signals and the
15 influence of unavoidable ambient light as well.

In present light-based wireless communication systems, first obvious
attempts have been made to handle the ambient-light problem. Usually, low
frequency (≤ 500 KHz) AC signals, which can be attributed to common
20 room illumination, are suppressed with electrical filters after the conversion
of light to electrical signals. Optical filters are used to restrict the spectrum
of undesired ambient light. However, a significant portion of daylight is
spectrally in the same range as the optical radiation of the light sources
appropriate for wireless communication systems.

25 As described in the above mentioned PCT patent applications PCT/EP
94/01196, and in another PCT application PCT/EP 94/00577, published on 31
August 1995 (Publication No. WO 95/23461), it is possible to provide an
infrared wireless communication system which efficiently copes with basic
30 problems, such as incident ambient light, for example, of commercially
available systems. In PCT/EP 94/01196 a scheme is provided which allows
the dynamic optimization of wireless optical communication systems
exposed to changing levels of ambient light.

1 Different schemes for wireless optical communication have been developed
and pushed by the active players in this particular field. This led to various
optical communication methods which are not compatible. It is, for example,
usually not possible to interconnect a computer of a first manufacturer with
5 the printer of a second manufacturer by means of a wireless optical channel,
because in most cases they operate in a different mode and the
transmitter/receiver hardware is not compatible.

Part of the incompatibility is caused by independent and uncorrelated
10 development efforts at the respective companies. Furthermore, there are
different applications that due to their nature call for different transmission
schemes (modes) to achieve adequate data rates and distance coverage.
Typical examples are: directed high-rate desktop links for computers and
peripheral devices, fixed- or variable data rate local area networks (LAN)
15 using diffuse radiation, remote control systems, low-rate paging functions,
and access links to wire-based systems and to wireless radio frequency (RF)
systems, such as cordless phones, for example. It is obvious that the
characteristics of these kinds of systems are dictated by the application
itself.

20 This means that certain different optical communication schemes will always
have to co-exist, i.e., that one has to cope with multi-mode systems.
However, it is to be expected that the differences caused by independent
and uncorrelated development efforts will disappear with time, or that at
25 least a standard will be defined such that most of the systems can
communicate with each other. An example of such a standard is the existing
IrDA standard. Work is going on to extend this standard. Details are given
in "Ease File Transfer With IrDA-Protocol Wireless Infrared", Bill Travis,
EDN, The Design Magazine of the Electronics Industry, July 1995, pp. 17-22.
30 In this article also the modulation method defined by the IrDA standard is
described.

1 A solution which accommodates the different requirements and needs of
current and future light-based communication systems and ensures their
coexistence and/or compatibility - within a common operating environment
(e.g. within a large area office) - is presently not available.

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It is thus an object of this invention to provide a wireless optical
communication system which enables multi-mode operation.

It is another object of this invention to provide a method and apparatus for
10 wireless multi-mode optical communication systems.

It is a further object of the present invention to solve typical problems of
current optical communication system, namely channel quality estimation,
frame/symbol synchronization and so forth.

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It is another object of the present invention to provide a method and
apparatus for wireless multi-mode optical communication systems which
works even under extremely bad channel conditions.

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SUMMARY OF THE INVENTION

The invention as claimed is intended to meet these objectives. It provides a
method and apparatus enabling wireless optical communication between a
25 transmitting station and a receiving station using a novel and inventive
robust physical layer header (RPLH). According to the present invention

1. said transmitting station provides a preamble comprising frames
forming a periodic sequence of pulses, i.e., a sequence of pulses with
30 defined period, the number of slots (L) per frame and the frame content
as such being known to said receiving station,

2. said transmitting station optically transmits said sequence of pulses,



- 1 3. said receiving station performs carrier detection based on said
sequence of pulses received,
4. said receiving station determines said period of the sequence of pulses
5 to obtain relative synchronization,
5. said receiving station adjusts its clock to the phase of the slots of the
received sequence of pulses, and clocks said incoming sequence of
pulses through a shift register,
- 10 6. said transmitting station transmits a unique synchronization word which
is aligned to the period of said preamble,
7. said receiving station correlates said sequence of pulses in said shift
15 register with said unique synchronization word known to it in order to
achieve absolute synchronization with said transmitting station upon
recognition of said synchronization word,
8. said transmitting station now indicates in a control field of predefined
20 length which modulation method will be used in the appended
data/subsystem field, such that said all receiving stations which are able
to support the respective modulation method wait for data to be
transmitted in this data/subsystem field.
- 25 It is to be noted that the sequence of the above steps is not mandatory.
Some of the steps can be also carried out in parallel.

Depending on the particular implementation, it is advantageous if the
transmitting station further indicates in said control field the length of the
30 appended data/subsystem field such that a receiving station can extract said
information to determine the time duration for muting its own transmitter to
avoid signal collision with the ongoing transmission (virtual carrier sense).
Under certain circumstances it is also useful to provide other control



1 information in said control field for communication link and network control.
Furthermore, information may be exchanged to allow negotiation and/or
adaptation of the data rate used for transmission. This allows to optimize
the throughput depending on the conditions (quality) on the channel. It is
5 also of advantage to provide priority-access information which allows
several co-existing pico-cells within one and the same communication cell.

Further advantages of the present invention and additional examples of
information which may be exchanged using the inventive robust physical
10 layer header follow in the detailed description.

The present invention can either be used for communication within a
single-mode system, i.e., for communication between stations supporting the
same modulation method, or for communication in a multi-mode system. To
15 ensure that multi-mode communication is possible, the respective hardware
according to the present invention has to be provided and any
communication has to be initiated according to the above steps.

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DESCRIPTION OF THE DRAWINGS

The invention is described in detail below with reference to the following drawings:

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FIG. 1 shows a table of different, co-existing IR subsystems (S1-S4) and a selection of typical applications.

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FIG. 2 shows an exemplary receiver of a multi-mode receiving station, according to the present invention, for operation within subsystems S1, S2, and S3.

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FIG. 3 is an exemplary schematic presentation of the multi-mode stations communicating within a communication cell, according to the present invention (Sx = subsystem, SxR = repeater for subsystem Sx).

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FIG. 4A shows a packet structure with robust physical layer header, according to the present invention.

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FIG. 4B shows an exemplary control field of the robust physical layer header and exemplary modulation method in the data/subsystem field (4-PPM in an S1 system), according to the present invention.

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FIG. 5 shows a schematic block diagram of a single-mode optical wireless communication system, according to the present invention.

FIG. 6 shows a schematic block diagram of an adaptive data rate (variable rate) system showing in particular the functional blocks for channel quality estimation and frame/symbol

1 synchronization (sync recognition), according to the present invention.

5 **FIG. 7** shows a simplified state transition diagram of the master state machine of Figure 6 for a system using rate reduction (RR) = 1, 2, 4, and 8.

10 **FIG. 8** illustrates a rate negotiation mechanism according to the present invention in conjunction with a standard CSMA/CA (carrier sense multiple access with collision avoidance) protocol.

15 **FIG. 9** shows an exemplary set of rate connectivity tables, according to the present invention.

FIG. 10 shows user network information derived from the rate connectivity tables of Figure 9.

20 **FIG. 11** shows a schematic block diagram of a portion of a receiving station for frame/symbol synchronization (part of 123 in Figure 12), according to the present invention.

FIG. 12 shows a schematic block diagram of a portion of a receiver, according to the present invention.

25 **FIG. 13** shows a simplified state transition diagram of a receiver containing the function of Figure 12 for a system using RR = 1, 2, 4, 8, through RR_{max} .

30 **FIG. 14** is a schematic illustration of a synchronization word for 4-PPM, according to the present invention, which is composed using two synchronization words.

GENERAL DESCRIPTION

1 In general, a system for wireless optical communication comprises at least one station serving as transmitter and a second one serving as receiver.
5 The transmitter comprises a light source, e.g. a light emitting diode (LED) or a laser diode, and the receiver comprises a photodiode. The word 'station' is hereinafter used as a synonym for all kinds of computers, terminals, repeaters, peripheral devices etc., which might communicate with each other. The present invention can also be used for communication
10 within a single-mode communication system, however, it is to be noted that the present invention is particularly well suited for communication in multi-mode systems.

Normally, infrared (IR) light is used for wireless optical communication and
15 the term 'IR communication' is used from time to time in the following, although the invention presented is not restricted to a specific range of the light spectrum.

1) THE INVENTIVE ROBUST HEADER:

20 Proposed is hereinafter an inventive header (described in more detail later) which is robust in the sense that it can be recognized and decoded by all receivers located within the same communication cell (e.g. office space) even under conditions when normal communication is not longer possible. Furthermore, the inventive robust header enables communication between
25 different stations co-existing in one and the same communication cell, i.e. communication between stations operating in different modes is enabled, coordinated and supported. The inventive robust header comprises a preamble for timing acquisition, carrier detection, and relative synchronization in the receiving station. It further comprises a unique
30 synchronization sequence to ensure absolute synchronization of transmitter and receiver upon recognition of the synchronization sequence in the receiver. Furthermore, it comprises a control field of fixed length transmitted following the synchronization word. This control field is

1 employed to provide the receiving station with information on supported
and/or expected user data rates, data block size, modulation method, and
other relevant (sub)system information. In particular, it may also comprise
information used to identify the recipient(s) (list of addressees) of the data
5 or information to follow after the robust header.

2) COMPATIBILITY/COEXISTENCE OF DIFFERENT TRANSMISSION SCHEMES:

Today, in a multi-mode system the signals transmitted by a transceiver of a
10 transmitting station in a certain mode (e.g. subsystem S1, see Figure 1)
cannot be received or understood by the receivers of any receiving unit in
another mode (e.g. subsystem S2) and vice versa.

In the following, the novel robust header, also referred to as robust physical
15 layer header (RPLH), which is designed to overcome the incompatibility of
co-existing systems, is further elaborated. Furthermore, the RPLH structure,
the methods devised for its use, corresponding transmitters and receivers,
and a resulting multi-mode wireless optical communication system are
described.

20

It is important that every station participating in the communication within a
communication cell transmits a RPLH if a data- or control packet is to be
transmitted. Each station within this cell belongs to a set of stations forming
a subsystem (Sx), according to a specific application, as illustrated in the
25 table given in Figure 1. If a station is equipped to participate in more than
one type of subsystem communication, then it is a member of all
corresponding subsystems. An example of a multi-mode receiver 35,
according to the present invention, of a station supporting the subsystems
S1, S2 and S3 is schematically illustrated in Figure 2. It comprises an
30 amplifier 30 and a photodiode 36 forming part of an analog frontend and
three bandpass filters 31-33, for example, for filtering the respective signals
received via the optical communication channel 14. The filter 31 (WBW) is
employed to extract signals used for subsystem S2 communication, filter 32

1 (VBW) is used for subsystem S1 communication, and filter 33 (SBW) for
subsystem S3. The output side of these filters 31-33 may be connected to a
digital processing unit 34.

5 Station 41 (A) in Figure 3, belongs to the subsystems S1 and S2, for
example, where S1 consists of the stations 41, 42, 43, 44, 46 (A, B, C, D and
F), and S2 consists of the stations 41 and 42 (A and B). A station can also
provide repeater functionality for some subsystems. Station 46 (F) in
Figure 3, for example, provides only repeater function for S1, which is
10 indicated by S1R, and station 42 (B) - besides being able to operate within
S1, S2 and S3 as a terminal - provides also a repeater function for S1 (S1R).
The size of a communication cell 40 is determined by the maximum
achievable transmission distance of the most robust of the participating
subsystems. Usually, this is the subsystem operating with the lowest data
15 rate, for example, the subsystem S4 providing pager functions.

The inventive robust header (RPLH) 50 is shown in Figure 4A. The RPLH 50
allows for a so-called virtual carrier sense (VCS) mechanism based on a
channel reservation time scheme. The inventive header 50 at least
20 comprises a preamble field 52 and a synchronization field 53 carrying a
preamble and synchronization word, respectively. Furthermore, it
comprises a control field 59 of predefined length. This control field 59 may
include information supporting adaptive (variable) data rate systems, as
described in the pending PCT patent application PCT/EP 94/01196,
25 published on 26 October 1995. Further details of the robust header's fields
will be given later.

The network of participating RPLH-based stations (multi-mode terminals and
repeaters) is controlled by the stations included in the subsystem with the
30 highest networking capabilities. This set of stations is called the supervisory
network (SN). In Figure 3, the SN is formed by stations 41, 42, 43, 44 and 46
(A, B, C, D and F), i.e. a variable data rate network is used as the SN in the
present example. Every station within a RPLH-based communication cell

1 which shall participate in the wireless optical communication must at least be equipped with a receiver frontend capable to receive and understand the RPLH in the modulation scheme used by the stations forming the SN.

5 The RPLH transmission, according to the present invention, is basically performed in two phases.

Phase 1: Every station within the RPLH range (communication cell 40) has its frontend activated for reception of the header. A station wishing to
10 transmit data waits until the SN channel is in idle state, then it sends the RPLH preferably including the information for VCS and mode. The other stations within said communication cell are listening to this message and process the transmitted information. If a modulation method is indicated in said robust header's control field 59 which a station is capable to support, it
15 stores the VCS information and remains active during phase two. Otherwise, it may set up its timeout counters based on the received VCS information and go into power-save mode, for example. The VCS information, i.e. the reservation time for the wireless channel, is derived from the data rate, block size, and the mode information indicated by the
20 transmitting station by transmission of the control field 59.

Phase 2: The remaining active receiving stations switch their receiver frontend to the mode indicated in the received control field 59 and determine the received destination address transmitted in said information
25 field 59 to determine if the message is for them. All stations not being addressed go into power-save mode, for example, and wait until the channel reservation time expires. The addressed station(s) may now communicate with the initiating (transmitting) station in its proprietary mode as long as the channel was reserved.

30

As described above, the present concept does not only allow for reliable carrier sensing in all receivers of a communication cell, including those with the lowest signal-to-noise ratio (SNR) budget, but they are also informed for

1 how long the channel will be occupied by the data block to be transmitted.
This principle, known as virtual carrier sensing (VCS) has been adopted and
optimized such that it can be used in combination with the present robust
header concept.

5

3) ROBUST HEADER FOR PULSE-POSITION MODULATION (PPM) SYSTEMS:
Further details of the robust header are given by means of an example. The
RPLH 50 of Figure 4A must be transmitted in a format complying with the
SN's modulation method. The RPLH 50 has to be decodable by every station
10 designed to participate within the RPLH-based communication cell. The
robust header should further help mitigate the so-called hidden terminal
problem. I.e., a header structure is to be defined which complies with the
respective SN's modulation method and which is suited to work even under
such hostile conditions where the SN (e.g. SN=S1) itself becomes
15 inoperable for data exchange while some of the subsystems (e.g. low-rate
pager functions) remain operational.

Exemplary embodiment of the inventive robust header:

For a variable-rate system, PPM is the scheme with the highest efficiency.
20 Therefore, we describe the structure of a RPLH for a PPM-based system, the
specific problems involved, and the proposed solutions. Details of a suited
control field 59 are illustrated in Figure 4B. The following description
assumes a communication system based on a specific PPM data symbol
format (i.e. 4-PPM symbols where two information bits are carried per
25 symbol), however, with appropriate adjustments the method is equally valid
for a system using different data symbol formats (e.g. L-PPM symbols where
 $\log_2(L)$ information bits are carried per symbol).

In this embodiment, the different parts of the robust header field 50, the
30 coding methods, and the number of transmitted symbols are given for a
variable data rate system based on the 4-PPM symbol format. The S1
subsystem of Figure 1 functions as the SN:

1 1. **PREAMBLE 52:**

 The preamble 52 is employed to obtain relative synchronization of the receiver. To achieve this, the preamble 52, which is a periodic sequence of pulses, is transmitted. The receiving station which knows
5 how many slots each frame comprises, is now able to detect after a certain while the period of said sequence of pulses. Furthermore, the receiving station adjusts its slot clock phase (clock recovery) using a clock recovery circuitry (phase locked loop PLL). It is recommended to use a pulse sequence leading to an as fast as possible slot clock phase
10 adjustment. For this purpose, we propose the pulse sequences 10001000... or 10000010..., either of which may be used for both 16-PPM and 4-PPM formats. Use of different sequences enables also simple (control) information transmission by means of the preamble alone.

15 2. **SYNCWORD 53:**

 The SYNCWORD 53 may comprise an encoded binary sequence (e.g. a 32-bit sequence) with selective autocorrelation and low cross-correlation with the preamble sequence 52. In the present example, each bit is mapped into four slots to preserve the same duty cycle as the preamble
20 sequence 52: if the bit is a "1", a pulse occurs in the first slot of the 4-PPM symbol; if it is a "0", the pulse is located in the third slot. Both slots are searched during reception for impossible bit combinations to improve the sync processing (e.g. correlation) result. Further details are described in connection with Figures 6 and 7. Another
25 synchronization word, composed from two separate synchronization words, is illustrated in Figure 14.

3. **RR (Rate Reduction) 54:**

 The RR field 54 is a word (e.g. four-bit) containing the rate reduction
30 parameter RR of the following data/subsystem field 51 (i.e. the field comprising data) in the case that the subsystem uses repetition coding. The rate reduction parameter indicates how often each pulse-position modulation symbol of the data/subsystem field 51 is repeated.

1 For other subsystems, it may serve as data rate indicator, for example.
The RR field 54 is transmitted as two symbols in 4-PPM format with
repetition coding.

5 4. RR* (Recommended Rate Reduction) 55:

The RR* field 55 is a word (e.g. four-bit) containing the recommended
rate reduction factor RR* as derived from the estimated channel quality
(error rate) during reception of the last data block (for subsystems
supporting channel quality estimation). It may be coded in the same
10 manner as RR.

5. BS (Block Size) 56:

The block size subfield 56 contains the number of data units which will
be transmitted in the data/subsystem field 51. To reduce overhead, one
15 can define only a limited number of different block sizes; for example,
sixteen different block sizes can be distinguished by corresponding
mapping of four bits. The block size subfield 56 may be coded in the
same manner as the RR symbols.

20 6. MODE 57:

The mode subfield 57 signals to the receiver(s) with which modulation
method the data in the data/subsystem field 51 will be transmitted and
whether the data/subsystem field 51 shall be forwarded through a
repeater. The number of mode bits is chosen large enough to be able to
25 admit future subsystems. The symbols may be coded in the same
manner as the RR symbols.

The information transmitted in the RR field 54 and BS field 56 can be used
to determine how long the transmission of the data in the data/subsystem
30 field 51 will take. This information is important for the receiving station not
being on the list of addressees, because they need to know how long the
optical channel will be occupied, i.e. how long they shall remain silent.

1 To minimize the effects of DC or low frequency components, analog
frontends of IR receivers are usually designed for AC coupling operation. A
varying symbol duty cycle would therefore require a costly (analog) DC
restoration. Furthermore, the transmitter's pulse amplitude and symbol duty
5 cycle must be chosen in accordance with the average- and peak power
constraints imposed on the IR light source; the latter usually exists in the
form of light emitting diodes (LEDs) or laser diodes emitting in the IR
spectrum.

10 The RPLH proposed as an example uses pulse patterns with the same duty
cycle as the 4-PPM data symbols to comply with the power constraints. The
same duty cycle may also be implemented in the synchronization field 53
rather than using a different duty cycle as is commonly done. As an
additional benefit, DC restoration needs not to be applied when using an
15 RPLH as proposed above. Should the resulting DC shift affect performance
to a degree where compensation is deemed to be necessary, one can use
the method of threshold control indicated in Figure 12.

Depending on the transmission scheme used, an algorithm may be
20 employed which determines the channel quality such that the maximum
possible data rate can be derived. Since the beginning of the
data/subsystem field is exactly known to all active receiving stations of the
communication cell(s), these stations can determine the channel quality by
analyzing the data received in said data/subsystem field 51. The maximum
25 possible data rate and other information concerning the status within the
communication cell may be displayed such that the user is informed at what
speed he can transmit data, for example.

According to the present invention it is possible that the robust header as
30 such is used to exchange information between certain stations in a
multi-mode communication cell if other communication methods fail. In this
case the throughput of information is very limited, however, some
information may still be transmitted.

1 In some cases it may be advantageous to transmit access priority
information within the control field 59 which is suited to distinguish
information of a first communication cell from information of a second,
interfering communication cell. Such a measure enables coexistence of
5 different simultaneously active communication cells (pico cells) within a
single cell 40 and each claiming the full channel capacity by ignoring the
virtual carrier sense information contained in the RPLH from other pico
cells. This is possible since the signal strengths within such a pico cell are
sufficiently high to allow channel capturing and thus remain unimpaired by
10 the interference from other distant pico cells. A pico cell may contain two
or more mobile or fixed stations and may also contain a station for access
to wired networks (LANs).

Figure 5 shows a first implementation of the present invention. According
15 to this implementation, the RPLH is generated if payload (binary data), or
information are to be sent over the optical channel 14. The RPLH is
generated by a header generator 10 whereas the binary data are processed
and encoded by a suitable encoder 11 used to map the binary data into
PPM symbols. In addition, a forward error correction system (not shown)
20 may be employed.

In the first implementation, the encoder is a pulse-position modulation
(PPM) encoder 11. A light emitting diode (LED) driver 12 feeds the signals
to be transmitted to a LED 17. The LED driver 12 may have a fanout of up to
25 eight devices, yielding a composite optical peak power of up to 2W, for
example. On the other side of the optical channel 14 there is a photodiode
18 (or an array of photodiodes) which receives the signals from the LED 17.
The output of the photodiode 18 is processed by the receiver's analog
frontend 13, for example comprising an amplifier and automatic gain control
30 (AGC) circuitry. Preferably, the analog frontend 13 should be designed to
prevent latch-up in the presence of high levels of ambient light, and the
AGC circuitry should offer a large dynamic range in excess of 70dB. Ruling
out soft demodulation to avoid the complexity of multi-bit processing, the



1 amplitude controlled analog signal provided by the frontend 13 of the
present embodiment is applied to a threshold device 15 (comparator) which
generates a binary-valued, continuous-time output signal. The output signal
is then processed by means of a digital processing unit 16. The latter at
5 least includes such functions as carrier sensing (carrier detection), slot
timing recovery and relative as well as absolute data symbol
synchronization by analyzing the fields 52 and 53 of the RPLH. Depending
on the information transmitted in the control field 59 of the RPLH, the digital
processing unit 16 may also provide for extraction of user data rate and
10 data block size, data decoding and channel quality estimation. An example
of the receiver's digital processing unit 16 is given and described in
connection with Figure 6.

In Figure 6, details of an embodiment of a receiver's digital processing unit
15 16 are shown. Upon receiving a preamble frames from the comparator 15,
first the slot clock is recovered by means of a first-order, digital
phase-locked loop (PLL) 60 with variable loop gain and preprocessing to
better cope with the noisy PPM signals. Phase estimates and subsequent
phase adjustment are based on n-times ($n=8$, for example) oversampling by
20 means of a slot sampler 61 of the binary-valued signal delivered by the
threshold device 15. The PLL loop gain is controlled by a master state
machine 63 (MSM). The operation of the MSM 63 is illustrated in Figure 7.
Preferably, the gain is set high at the beginning of preamble reception to
obtain fast phase acquisition and to reduce the probability of a hang-up
25 condition of the PLL 60. To prevent the local clock phase from slipping
during tracking of the received signal phase, the loop gain is changed to a
lower value after correct detection of carrier and preamble data by the
carrier sense circuit, according to the present implementation. The PLL 60
locks on the rising edge of the input signal and the recovered slot clock
30 (e.g. 4 MHz) is adequately delayed to serve as reference for the slot
sampler 61. A sampling clock's phase resolution of 45° is sufficient for slot
sampling without performance degradation. The remaining parts of the
circuits are timed with the recovered slot clock (e.g. 4 MHz). Symbol



1 synchronization is accomplished in two steps. The sequence of events
follows the simplified state diagram of the MSM 63 shown in Figure 7.
Following carrier detection, a carrier sensing circuit searches for proper
preamble pattern and informs the MSM 63 when a valid pulse sequence of
5 preamble 52 was found. In return, the MSM 63 enables a symbol
synchronization circuit inside the sync recognition box 62 by providing a
trigger signal aligned with the preamble phase (position of preamble pulse),
corresponding to the first slot of the specially coded synchronization word.
From here on, the frame synchronization circuit being part of the sync
10 recognition box 62 stores the information found in consecutive 32 symbol
frames in a 32-bit shift register inside box 62 whose outputs are fed into a
correlator (it is to be noted that in the present example we assumed that the
syncword has 32 bits). Further details of the sync recognition unit 62 are
given in Figure 11. If the received pulse sequence fed into the shift register
15 is found to be the same as the one already known to the receiver, absolute
synchronization is achieved, i.e. the MSM 63 assumes that the beginning of
the control field 59 of fixed length just ahead of the PPM-encoded data block
has been found. In order to indicate that absolute synchronization has been
achieved, a sync-flag is provided at the output line 67 of the box 62.

20

Likewise, one may also employ an algorithm and suited syncword 53 which
allows absolute synchronization even if the received syncword is partially
corrupted. An example of such a synchronization word is given in
Figure 14, and a suited receiver hardware is illustrated in Figure 11. E.g., if
25 the correlator 112 result, computed for every symbol frame period where a
synchronization pulse can be expected, exceeds a certain threshold T_{th}
(see box 113), the MSM 63 may assume that the beginning of the control
field 59 has been found. The syncword 53 as such may also carry additional
information, as addressed later.

30

If the beginning of the control field 59 of fixed length has been found, the
beginning of the data/subsystem field 51 is known, too. According to the
present example, where the data/subsystem field 51 is PPM-coded, all of the

1 the following symbols are thus interpreted as PPM symbols. Each field
54-57, as shown in Figure 4B is frame-wise accumulated (e.g. 16 times) in
the pulse accumulator 64 and evaluated by a suited symbol evaluation
circuit 65. The same procedure may be used for data detection in the
5 data/subsystem field 51 according to the RR information received in the
control field 59. There are different ways conceivable how the information
carried in the control field 59 can be decoded and transmitted. The receiver
has to be designed accordingly.

10 If the entire data/subsystem field 51 is correctly received, a trigger signal
for incrementing the throughput measurement circuit may be generated and
the packet success rate counter is reset.

A channel quality estimator 66 supervises the error rate on the IR channel
15 14. In the present implementation, a digital channel quality estimator 66 is
employed because SNR determination by means of analog circuitry or
packet success rate measurements are either costly or slow and are thus
less well suited. The channel quality estimator 66 supervises the error rate
on the IR channel 14. From this estimated error rate the recommended rate
20 reduction factor (RR^*) for future data/subsystem fields 51 may be
determined. For a fast feedback response to the transmitter of the
transmitting station, transmission error counting may be done at the PPM
symbol level rather than at the data/subsystem field level. Obviously
incorrect PPM symbols (i.e., 0, 2, 3, ... pulses per frame) are counted by
25 observing every received symbol individually. The ratio of observed symbol
errors and the total number of symbols received in a data/subsystem field
51 is then taken as a measure of the instantaneous error rate on the IR
channel 14.

30 In the following, examples of a scheme for rate negotiation are given. The
maximum possible data rate achieving essentially error-free packet
transmission (erroneous packets are repeated on the level of the medium
access control protocol) may vary over a wide range within a short time.

1 Those stations which are able to adapt their data rate need to interchange
their currently suitable data rates. To prevent repeated retransmissions, this
exchange of rate information may be done within the error feedback
message.

5

According to the proposed rate negotiation method, every station transmits
the recommended rate reduction (RR*) parameter based on the last
received dataframe in the corresponding field of the RPLH. It is illustrated in
Figure 8 how the procedure of rate negotiation may be implemented in a
10 CSMA/CA (carrier sense multiple access/collision avoidance) protocol using
Request-To-Send/Clear-To-Send (RTS/CTS). The proposed rate negotiation
is based on the following principles:

• The channel quality is estimated based on all received data and control
15 frames for which the total number of L-PPM symbols exceeds 128.

• The data rate, especially for control frames, is adapted conservatively
to prevent unnecessary retransmissions caused by damaged CTS
frames or acknowledgement (ACK) frames. Retransmissions are
20 appropriate when collisions occurred and when the channel SNR
(signal-to-noise ratio) is high. In cases of low channel SNR, repetition
coding (i.e. increasing RR) is more efficient.

• A mandatory ACK frame is introduced to transmit the recommended
25 rate reduction symbol and to ensure that only one retransmission of
the data block will be necessary.

• To alleviate the carrier sense problem, a network allocation method
(similar to that in IEEE 802.11) may be used. The reservation
30 information should be transmitted with the highest possible
redundancy. For an adaptive rate transmission system we propose that
the actual channel reservation time be calculated by means of the rate

1 symbol (RR) and the data block size (BS) transmitted in the control
field 59.

5 The network initialization within a communication cell (see for example
Figure 3) can take place as follows: One station with S1 capability initiates
the network start-up by transmitting a special control frame which is defined
for every subsystem. This happens first for S1, then the initiating station
waits until it got responses from all other S1 stations. The initiating station
proceeds in the same manner for S2 and S3. Upon completion, all other
10 stations proceed the same way - each for its respective subsystems -
according to the chosen channel access protocol. At the end, all stations
transmit their list of asserted connections to every station on their list. By
this method each station obtains a status map of every possible connection
in the network, including initial channel quality information. These maps are
15 herein referred to as rate/connectivity status maps. Based on this
information hidden terminals within the communication cell may be
identified. Furthermore, during network initialization one may also transmit
information which is important for receiving stations to know. The length of
the control field 59, details on the subfields of the control field 59, and so on
20 can be defined during network initialization.

For both user information and network control some kind of
rate/connectivity tables (RCT) 90-92 should be stored in every station and
displayed to the user in an effective way. The information of such a
25 rate/connectivity table may also be made available to an application
program if needed. The exemplary RCTs 90-92 in Figure 9 are composed
from the rate/connectivity status maps. The RCTs may be used for user
information, as illustrated in Figure 10, network reorganization, and
alternative routing through repeaters. Furthermore, an RCT helps
30 increasing network throughput because the initial data rates are known.
After some time, the RCTs may need to be refreshed because some S1
station adapted the data rate, stations physically moved, or new stations try

1 to join the network, for example. In the latter case, another initialization procedure must be executed.

5 The example of displayed user network information for station D shown in Figure 10 illustrates that station D cannot be received by station B, i.e. station D represents a hidden terminal for station B. In the present example, the display 101 shows a corresponding message recommending rectification of the situation. Furthermore, the example display 100 shows that communication between stations D and A is limited to a relatively low data
10 rate. As shown in the second display 101 of Figure 10, this implies that a 1.6 MB file transfer would need two minutes to complete. Thus, the recommendation to move closer to station A is displayed to user D.

Excessive header overhead in high-rate systems may be avoided as follows.
15 Stations operating in a subsystem using low-rate transmission (e.g. pager function S4) require a much lower SNR and thus exhibit a much higher robustness against noise (up to 20-30 dB higher) than the chosen SN ($SN=S1$). Using repetition coding algorithms and a suited symbol synchronization scheme a RPLH can be designed which has high enough
20 robustness for low-rate transmission. However, the required length of such a header would drastically decrease the performance of the SN and other high-rate subsystems. An example of such a header with a synchronization word of increased length used to obtain improved robustness is described in connection with Figure 14.

25

Investigations on implementation complexity (cost) and transmission efficiency versus robustness of the system lead to a dual-mode RPLH scheme. A so-called low-rate-reduction-mode RPLH (L-RPLH) supports rate reduction (RR) factors up to eight in SN transmission mode. A more costly
30 high-rate-reduction-mode RPLH (H-RPLH) enables SN communication with a maximum RR of 64. The H-RPLH supports subsystems operating at SNRs up to 20 dB below the SNR required to sustain acceptable packet success probability on a SN link operating without rate reduction (i.e. $RR = 1$). The

1 networks in SN (S1) and high-rate (S2) transmission mode use normally the
L-RPLH and they only activate the H-RPLH when low-rate transmission (S3)
and/or remote control functions (S4) are announced within the
communication cell. With this scheme, and assuming robust direct carrier
5 sensing circuitry is active in the H-RPLH stations, upcoming L-RPLH traffic
can be announced to every station within H-RPLH range, even in case
where the header itself cannot be correctly decoded. Network initialization
and initial channel quality estimation for SN stations are performed in the
H-RPLH mode.

10

To achieve high reliability (robustness), the receiving stations may
determine the header mode (L-RPLH or H-RPLH) by analyzing the periodic
pattern of the received preamble by means of a pulse averaging procedure
(please note that this is not the preamble's primary use according to the
15 present invention). For example, averaging the received preamble stream
sixteen times or more times allows for reliable mode detection down to a
SNR of 0 dB (where an RR of 64 is required for reliable detection of the data
field 51). For example, the preamble pulse sequence 10001000..., having a
period of eight slots (length of two 4-PPM symbols), may be used to signal
20 that the header mode is H-RPLH, and the preamble pulse sequence
10000010..., also having a period of eight slots, may signal that the header is
L-RPLH. The same circuit used on the receiver side for header mode
detection can be also used for robust direct carrier sense detection.

25 Frame synchronization is required to determine the beginning of the control
field 59 and the beginning of the following - possibly repetition coded -
data/subsystem field 51. It is also the basis for deduction of the PPM symbol
boundaries if PPM-coded transmission is used. For these purposes, a
special pulse pattern 53 may be transmitted immediately after the preamble
30 52 (see Figure 4A). Common solutions use illegal PPM symbols (e.g. more
than one pulse per symbol) to make the synchronization word 53 uniquely
detectable or they detect a suitable binary sequence (showing desirable
correlation properties) by means of a correlator circuit. However, a single

1 synchronization word 53 working under H-RPLH conditions may have to be
excessively long, requiring a correspondingly long correlator circuit. A
further problem is that the synchronization word 53 must be embedded
within the chosen PPM format to comply with the average power constraints
5 imposed by the IR light source (duty cycle) and to maintain continuity in the
received DC-level.

A solution which preserves the duty cycle, avoids DC-level shift, and
reduces the required correlator length under H-RPLH conditions will now be
10 described in connection with Figure 11. Rather than using a long, single
synchronization word 53, two relatively short synchronization words may be
used to compose a suitable, longer synchronization word. The first one is
embedded within the chosen PPM symbol format in such a way that the
corresponding first correlator 110 produces ideally, i.e. in the absence of
15 noise, an output corresponding to a second specified synchronization word.
The output of this first correlator 110 is then used as the input for a
corresponding second correlator 112 who provides the symbol/frame
synchronization information after applying a threshold operation 113 to its
output. This scheme remarkably reduces the hardware expense for
20 synchronization detection. Furthermore, this scheme is compatible with the
dual-mode header transmission method (L-RPLH or H-RPLH).

The two-stage synchronization scheme described below can be extended
such that additional information can be conveyed jointly with the
25 synchronization information. For example, the second synchronization word
is used in 4 different ways (i.e. for example, $B_1 = \{ +1, +1, -1, +1, -1 \}$,
 $B_2 = \{ -1, +1, -1, +1, +1 \}$, $B_3 = \{ -1, -1, +1, -1, +1 \}$,
 $B_4 = \{ +1, -1, +1, -1, -1 \}$) such that 2 different second-stage correlators
can distinguish the 4 resulting composite synchronization sequences (we
30 assume here that every version of the second synchronization word has a
complementary version). The 4 resulting sequences at the output of the first
correlator should have good auto-correlation and cross-correlation
properties. This scheme can convey 2 bits of information jointly with the

1 synchronization information. Similarly, the scheme can be generalized for
example by including the first synchronization word to convey additional
bits of information.

5 In the following, further details on a possible two-stage synchronization
scheme and symbol/frame synchronization for low SNR are given.
Figure 11 illustrates the above mentioned two-stage correlation scheme for
frame and symbol synchronization in case of low SNR. In this example, the
first correlator 110 is designed to respond to a binary valued first
10 synchronization word. The output of the first correlator 110 is ternary valued
(+1, 0, -1) by circuit 111 and provides the input for the second correlator
112. The second correlator's output is again binary valued (0, +1) by
circuit 113 and feeds a storage element 114 controlled by the slot clock of
the PPM system; the signal Sync_flag at output 67 represents the
15 synchronization information.

Another implementation of a receiver, according to the present invention
and a corresponding state diagram are given in Figures 12 and 13. This
receiver has the desirable property to provide a fast (at medium to high
20 SNR) as well as a robust (at low SNR) carrier detection function. As
illustrated in Figure 12, there are two threshold detectors 121 and 124. The
latter one is for fast carrier detection, whereas the first one is for robust
header detection 123 as well as data detection 122. The robust header
detector 123 provides the signal Preamble_flag to the functional block 126,
25 called carrier assertion, for the purpose of asserting the signal
Fast_Carrier_flag provided by the fast carrier detector 125. While the
Fast_Carrier_flag signal provides fast carrier detection at medium to good
SNRs, the Preamble_flag signal provides a slower signal for carrier
detection at low SNR. Combined together, the two signals
30 (Fast_Carrier_flag, Preamble_flag) provide robust as well as fast detection of
the carrier. Box 126 generates the signal Carrier_flag (indicating successful
carrier detection) from these two signals. In cases where Preamble_flag
does not occur within a certain time after Fast_Carrier_flag is raised, a false

1 alarm is declared and Fast_Carrier_flag (and thus the Carrier_flag) is reset
by means of the signal Fast_Carrier_reset.

The robust header detector 123 provides the signals Header_flag,
5 Block_size, Sync_flag, RR, L (mode) and probably others - depending on the
fields transmitted in the control field 59 - to other functions of the receiver
not shown.

Since knowledge of RR after reception of the control field 59 within the
10 robust header 50 indicates the channel quality (SNR), this information
together with information on the modulation method can be used to adjust
the threshold value v_{TH2} of comparator 121 to an optimal value during
reception of the data/subsystem field 51. (N bit feedback from 123 to 120).
The threshold v_{TH1} of comparator 124 is chosen for optimal fast carrier
15 detection.

In Figure 14, a synchronization word being composed of two shorter
synchronization words (sequence 1 and sequence 2) is illustrated. This
Figure illustrates how a PPM transmitter according to the present invention
20 composes such a long synchronization word from the first word (S) and the
second word (B). Additionally, it is shown in what order the synchronization
word is transmitted within 4-PPM symbol frames. This long synchronization
word composed of two shorter ones as well as similar synchronization
words are suited for use if the quality of the transmission channel is poor.
25 Thus, this method of symbol/frame synchronization is well suited to enable
the design of a robust header in practice. Correct synchronization is
possible (through correlation detection) even in the case where only part of
the synchronization word is received correctly.

30 According to the present invention, a user is free to transmit encrypted data
within the data/subsystem field 51, however the robust header 50 should
never be encrypted so that all stations can understand it when received
from any of the participating stations. The inventive concept allows

1 encryption of the information transmitted in the data/subsystem field 51
since there are no restrictions as to what the data/subsystem field has to
look like.

5 It can make sense, however, to include in the control field 59 a sub-field
(similar as for the access priority information or mode field) which can be
used to indicate to the destination (receiving station) and possibly other
stations that the following data/subsystem field will be transmitted in
encrypted mode (generally encryption is handled above the physical layer).

10 More generally, one may specify in the control field 59 a "generic" sub-field
of which every station knows that it is there (including position and length),
but the meaning of its content only being known to a subset of stations.
Inclusion of such a generic sub-field in the control field 59 of the robust
15 header 50 demonstrates that the robust header concept even tolerates some
individual degree of freedom without compromising its main intent, namely
that it can be understood by all and in particular under very poor channel
conditions.

20 In the following, examples of different implementations of the present
invention will be outlined:

1. Hardware according to the present invention may for example be
integrated into a computer card which either may be connected to a
25 computer bus by installing it inside the computer's housing, or which
may be plugged into a slot (e.g. in form of a Personal Computer
Memory Card International Association (PCMCIA) card) provided in
said housing.

30 2. Likewise, the present transmitter/receiver may be provided in a
separate housing which is to be connected to a computer.

- 1 3. Furthermore, a transmitter/receiver according to the present invention
may be integrated into a peripheral device (e.g. a printer). In some
cases a lightweight version is sufficient, since usually a peripheral
device such as a printer for example is only receiving data. Only a
5 limited amount of information is normally fed back to the station which
requested a print job. In such cases it may be sufficient just to transmit
the robust physical layer header and some information in the header's
control field.
- 10 4. The inventive scheme may also be implemented in the form of
microcode for execution on a digital signal processor or another special
purpose hardware engine.

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CLAIMS

1. Method enabling wireless optical communication between a transmitting station and a receiving station, whereby
- a) said transmitting station provides a preamble (52) comprising frames forming a periodic sequence of pulses with defined period, the number of slots (L) per frame and the frame content being known to said receiving station,
 - b) said transmitting station optically transmits said sequence of pulses,
 - c) said receiving station performs carrier detection based on said sequence of pulses received,
 - d) said receiving station determines said period of the sequence of pulses to obtain relative synchronization,
 - e) said receiving station adjusts its clock to the phase of the slots of the received sequence of pulses, and clocks said incoming sequence of pulses through a shift register,
 - f) said transmitting station transmits a unique synchronization word (53) aligned to said period, said unique synchronization word (53) being known to said receiving station,
 - g) said receiving station correlates said sequence of pulses in said shift register with said unique synchronization word known to it in order to achieve absolute synchronization with said transmitting station upon recognition of said synchronization word (53),
 - h) said transmitting station now indicates in a control field (59) of predefined length and structure, which modulation method will be used for transmission of data in a data/subsystem field (51), such that said all receiving stations which are able to support the respective modulation method wait for said data.
2. The method of claim 1, whereby a receiving station capable to support different modulation methods, switches its receiver to the respective modulation method indicated in said control field (59).

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- 1 3. The method of claim 1, whereby either said control field (59), or said data/subsystem field (51) comprises a list of addressees for said data.
- 5 4. The method of claim 1, whereby pulse-position modulation (PPM) is used as modulation method for the transmission.
- 10 5. The method of claim 4, whereby said control field (59) comprises a rate reduction field (RR; 54) which indicates to said receiving station how often each pulse-position modulation (PPM) symbol of said data/subsystem field (51) will be repeated.
- 15 6. The method of claim 1, whereby said control field (59) comprises a recommended rate reduction field (RR*; 55) for transmission of a recommended rate reduction (RR*) which is employed to negotiate a data rate best suited for communication.
- 20 7. The method of claim 6, whereby said recommended rate reduction (RR*) is determined based on pre-defined rules taking into account the actual error rate which occurred during the communication between transmitting station and receiving station.
- 25 8. The method of claim 1, whereby said control field (59) comprises a block size field (BS; 56) indicating the number of data units which will be transmitted in said data/subsystem field (51).
- 30 9. The method of claim 1, whereby said control field (59) comprises a mode field (57) which carries information used to indicate to said receiving station which modulation method will be used, i.e., which set of stations forming a subsystem are addressed.
10. The method of claim 9, whereby said modulation method is either
- 4-slot pulse-position modulation (4-PPM),
 - 16-slot pulse-position modulation (16-PPM), or

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- 1 • the modulation methods defined in the IrDA standard.
11. The method of claim 1, whereby said control field (59) comprises
information signaling to said receiving station whether said data shall
5 be forwarded by said receiving station (repeater function).
12. The method of claim 1, whereby said control field (59) comprises
information which allows any receiving station not being addressed, or
not being able to support the modulation scheme indicated in said
10 control field (59), to determine how long the transmission of said data
will take to ensure that these receiving stations remain silent during this
transmission.
13. The method of claim 1 or 4, whereby said receiving station uses an
15 algorithm for recognition of said synchronization word (53) even in the
presence of potential errors caused by corrupted optical
communication.
14. The method of claim 13, whereby said synchronization word (53)
20 consists of two synchronizations words such that the recognition at the
receiving station can be split into two stages.
15. The method of claim 1, whereby said receiving station and/or
transmitting station determine the data rate at which said data are to be
25 transmitted.
16. The method of claim 1, whereby said receiving station determines a
recommended data rate to be used for transmission of said data, taking
into account the current quality of the communication channel between
30 transmitting station and receiving station, said recommended data rate
being determined based on the knowledge when exactly the control
field (59) ends and thus said data/subsystem field (51) starts.





- 1 17. The method of claim 15 or 16, whereby said data rate and/or recommended data rate information is made available to an application program or an end user.
- 5 18. The method of claim 1, whereby said control field (59) comprises access priority information allowing at least two co-existing communication subcells (pico-cells) within a communication cell (40).
- 10 19. The method of claim 1, whereby said control field (59) comprises information supporting encryption of said data.
20. Multi-mode packet (50, 51) for wireless optical communication between a transmitting station and a receiving station, said multi-mode packet (50, 51) comprising
- 15 • a pulse-position modulated (PPM) data/subsystem field (51) which carries data to be transmitted, and
- a preceding robust physical layer header (RPLH; 50) employed to enable communication even under adverse conditions, said robust physical layer header (RPLH; 50) comprising:
- 20 a) a preamble (52) with frames forming a periodic sequence of pulses with defined period, the number of slots per frame and the frame contents being known to said receiving station,
- b) a unique synchronization word (53) being known to said receiving station,
- 25 c) a control field (59) of predefined length and structure comprising mode information indicating which modulation method is used for the transmission of said data, and a rate reduction field (RR; 54) which indicates to said receiving station how often each pulse-position modulation (PPM) symbol of said data/subsystem field (51) will be repeated.
- 30





- 1 21. The multi-mode packet (50, 51) of claim 20, whereby either said control field (59), or said data/subsystem field (51) comprises a list of addressees for said data.
- 5 22. The multi-mode packet (50, 51) of claim 20, whereby said control field (59) comprises a recommended rate reduction field (RR*; 55) for transmission of recommended rate reduction (RR*) information which is employed to negotiate a data rate best suited for communication.
- 10 23. The multi-mode packet (50, 51) of claim 20, whereby said control field (59) comprises a block size field (BS; 56) indicating the number of data units which will be transmitted in said data/subsystem field (51).
- 15 24. The multi-mode packet (50, 51) of claim 20, whereby said control field (59) comprises information signaling to said receiving station whether said data shall be forwarded by said receiving station (repeater function).
- 20 25. The multi-mode packet (50, 51) of claim 20, whereby said control field (59) comprises information which allows any receiving station not being addressed, or not being able to support the modulation scheme indicated in said control field (59), to determine how long the transmission of said data will take to ensure that these receiving stations remain silent during this transmission.
- 25 26. The multi-mode packet (50, 51) of claim 20, whereby said control field (59) comprises information supporting encryption of said data.
- 30 27. Transmitter for wireless optical communication with a receiving station, comprising
- a) a header generator providing a preamble (52) with frames forming a periodic sequence of pulses with defined period, the number of





- 1 slots per frame and the frame content being known to said receiving station,
- b) means for providing a unique synchronization word (53) being known to said receiving station,
- 5 c) means for providing a control field (59) of fixed length and known structure, said control field (59) indicating the respective modulation method which will be used for transmission of data,
- d) means for modulating said data to be transmitted, and
- e) means for transmitting said sequence of pulses followed by said
- 10 unique synchronization word (53) being aligned to said sequence of pulses, said control field (59), and said modulated data.
28. The transmitter of claim 27, further comprising means to provide a list of addressees for said data to be transmitted, said list of addressees being
- 15 either provided within said control field (59) or said data/subsystem field (51).
29. The transmitter of claim 27, further comprising means to generate a data field (DSF) using the previously received recommended rate
- 20 reduction (RR*) for transmission of data, and transmits in said control field (59) its own recommended rate reduction (RR*) being used to negotiate a data rate best suited for communication.
30. The transmitter of claim 27, further comprising means for indicating the
- 25 number/size of said data to be transmitted.
31. The transmitter of claim 27, further comprising means for signaling to said receiving station whether said data shall be forwarded by said receiving station (repeater function).
- 30
32. Receiver for wireless optical communication with a transmitting station which transmits





- 1 • a preamble (52) with frames forming a periodic sequence of pulses
with defined period, the number of slots per frame and the frame
content being known to said receiver,
- 5 • a unique synchronization word (53) known to said receiver,
- a control field (59) of fixed length and known structure, indicating
the respective modulation method which will be used for
transmission of data,
- said receiver comprising:
- 10 a) means for determining said period of the sequence of pulses, based
on the number of slots per frame and the frame content being
known to it, in order to obtain relative synchronization,
- b) means for carrier detection based on said sequence of pulses,
- c) means for adjusting the receiver's clock to the phase of the slots of
said sequence of pulses received,
- 15 d) means for clocking said sequence of pulses received through a shift
register the length of which is defined by said unique
synchronization word (53),
- e) means for correlating said sequence of pulses in said shift register
with said unique synchronization word known to it in order to
20 achieve absolute synchronization with said transmitting station upon
recognition of said unique synchronization word (53),
- f) means to determine from said control field (59) whether the receiver
is able to support the respective modulation method which will be
used for the transmission of said data,
- 25 g) means which determine from the information received whether the
receiver is the right recipient for said data, and
- h) means enabling the receiver to receive said data right after the end
of said control field.
- 30 33. The receiver of claim 32, further comprising means to switch between
one, two or more modulation methods.





- 1 34. The receiver of claim 32, wherein said means to achieve absolute
synchronization comprise a first and a second correlator such that a
synchronization word (53) generated using two synchronization words
can be recognized in two stages.
- 5 35. The receiver of claim 32, further comprising means to determine a
recommended rate reduction (RR^*), derived from channel quality
estimation, being used to negotiate a data rate which is best suited for
the transmission of said data.
- 10 36. The receiver of claim 32, further comprising means for determining the
number/size of said data to be expected, analyzing information
transmitted in said control field (59).
- 15 37. The receiver of claim 32, further comprising means for retransmission of
said data if the received information indicates that retransmission is
required (repeater function).
- 20 38. Multi-mode wireless optical communication system comprising at least
one transmitter according to any of the claims 27-31 and one receiver
according to any of the claims 32-37.
- 25
- 30

Subsystem name attribute		Data rate	Modulation	Range	Environment	Application
S1	Variable-rate (supervisor node=SN)	64kb/s ... 4Mb/s	4/16-PPM	5-10m diffuse	All office	Ad-hoc networking, device- sharing
S2	High-rate	4- 10Mb/s	4-PPM, Man- chester	1-2m direct LOS	Desktop	CD-ROM, Scanner, File- transfer
S3	Low-rate	8- 16kb/s	4/16-PPM, FM, PSK	<25m diffuse	All office, shop floors, lobby, factory	Paging, data- collection
S4	Remote Control	<1kb/s	various	<15m diffuse	Home	TV, Audio, Video

FIG. 1

2/13

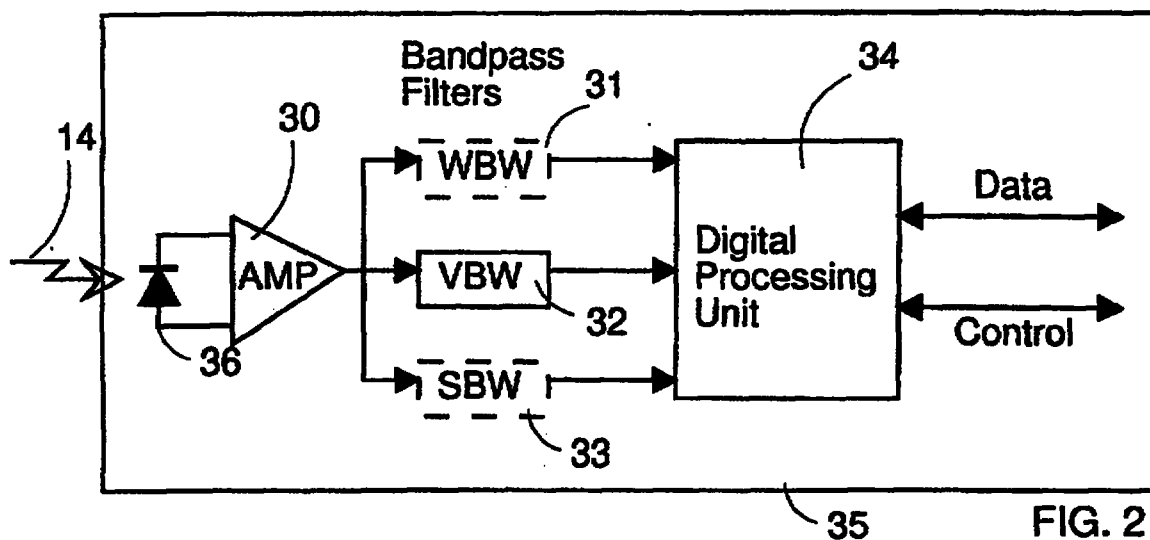


FIG. 2

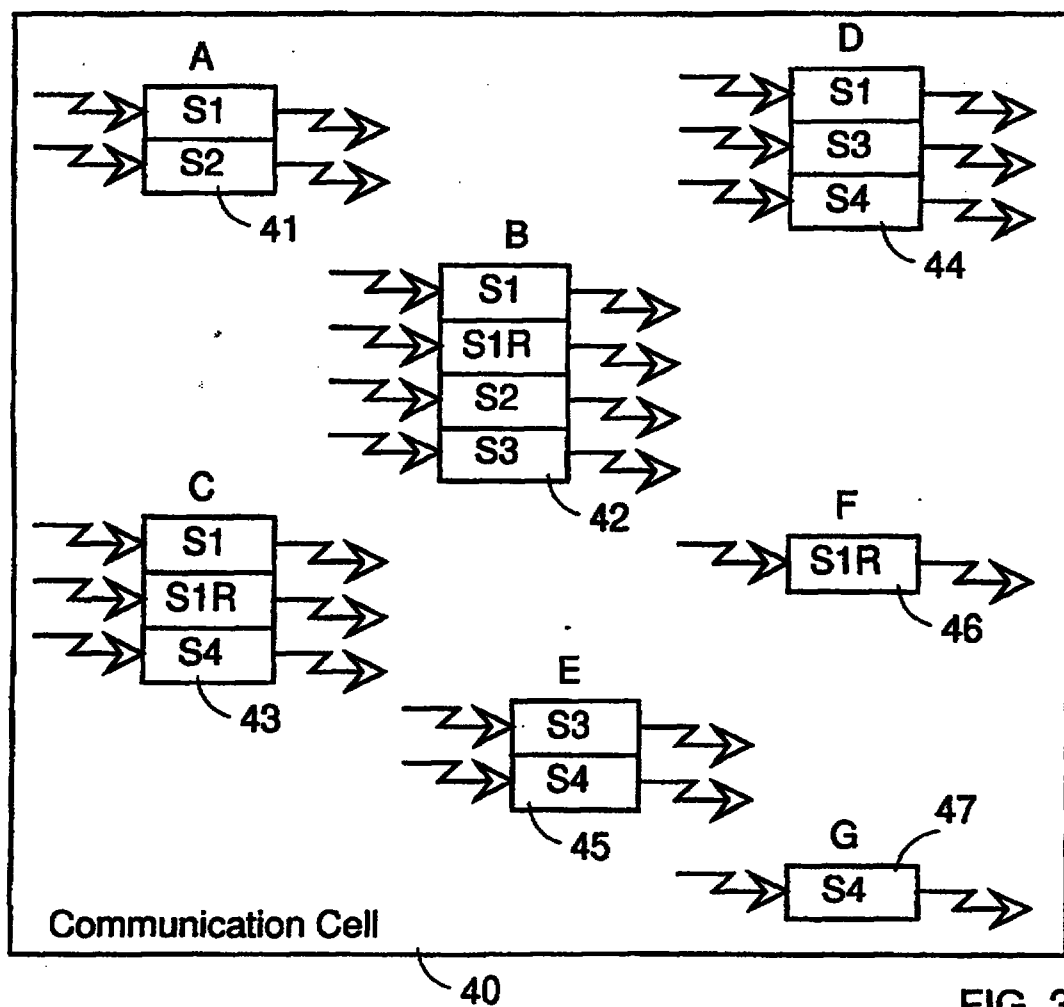


FIG. 3

3/13

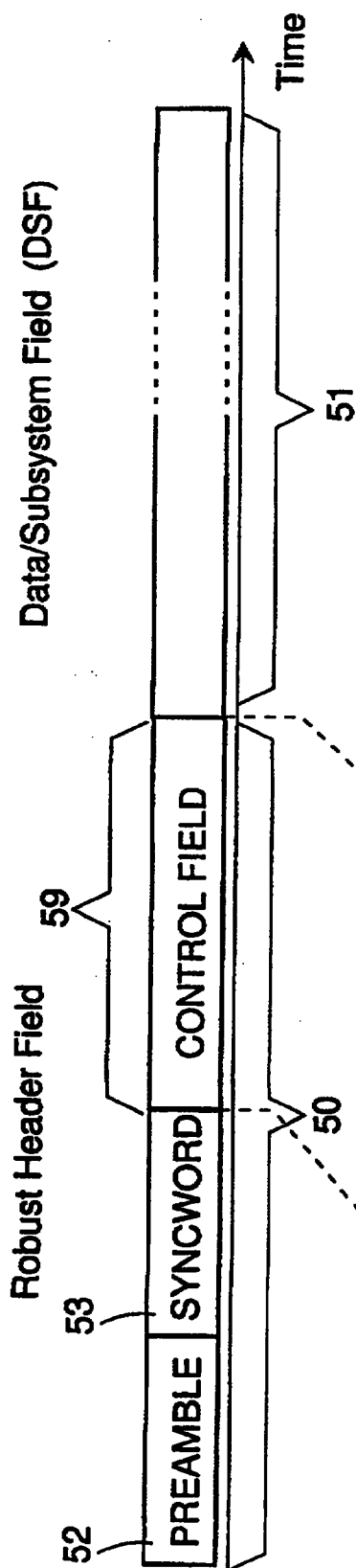


FIG. 4A

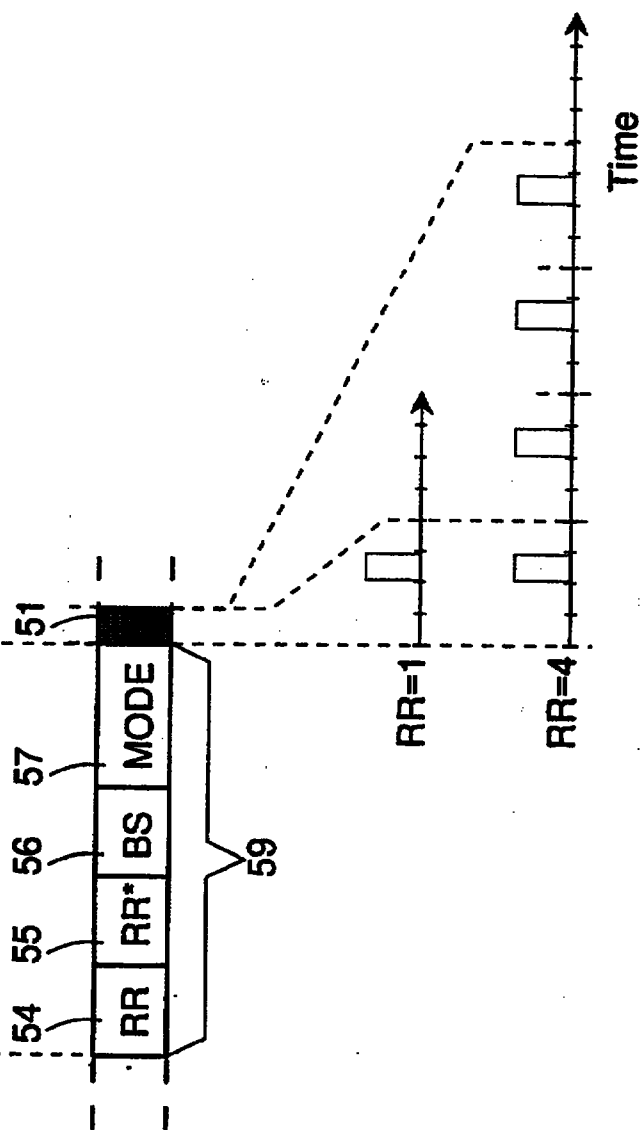


FIG. 4B

4/13

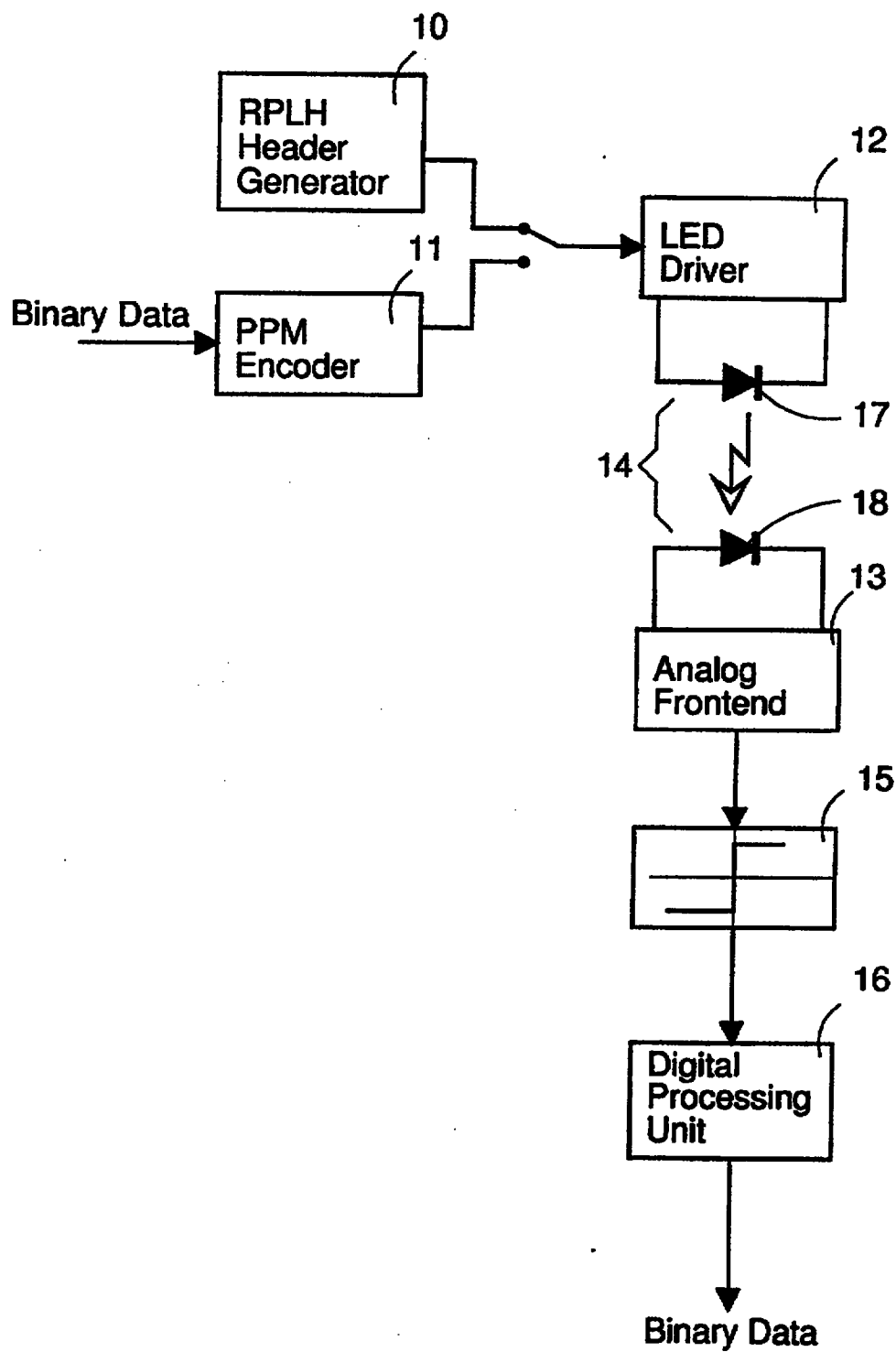


FIG. 5

5/13

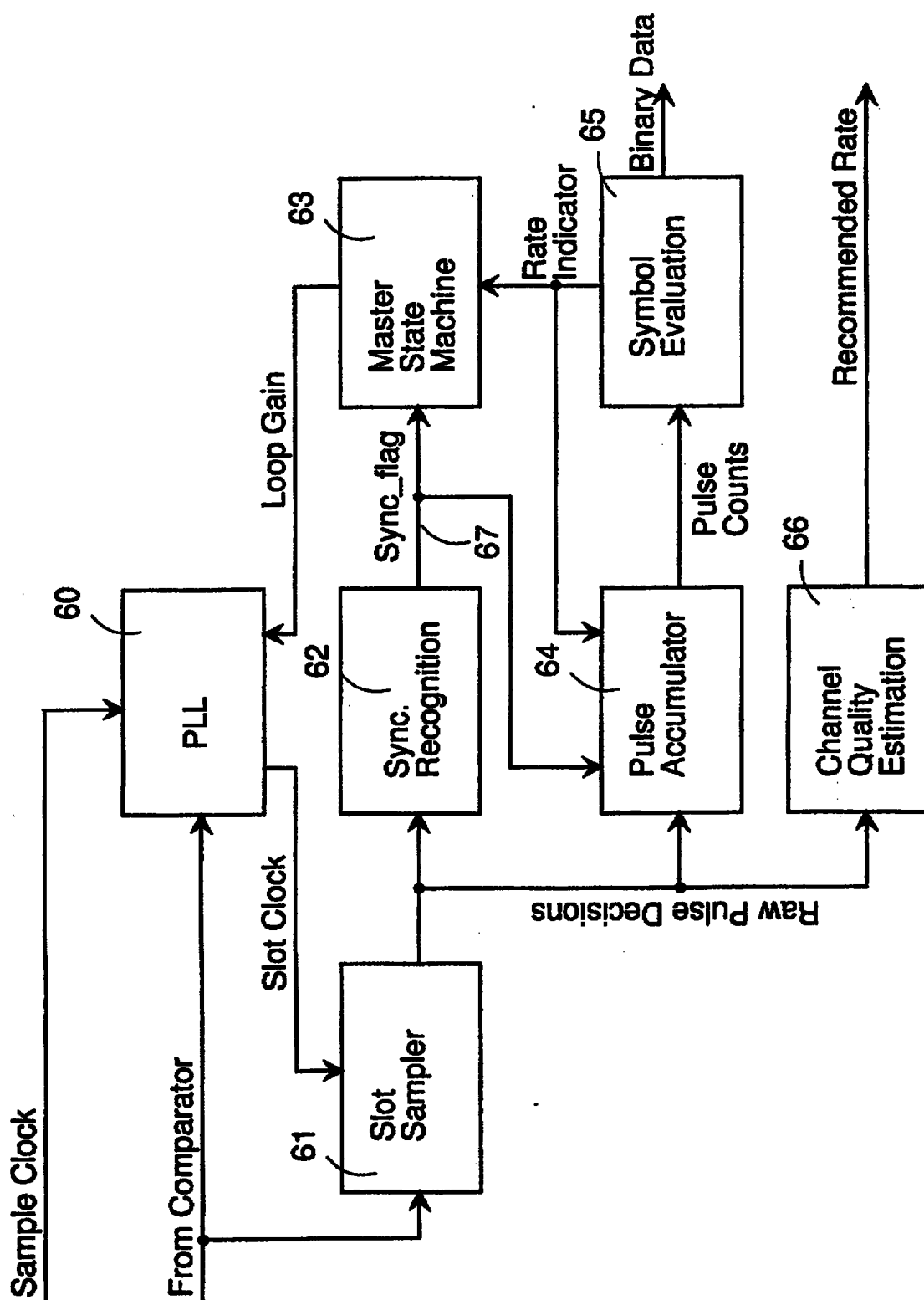


FIG. 6

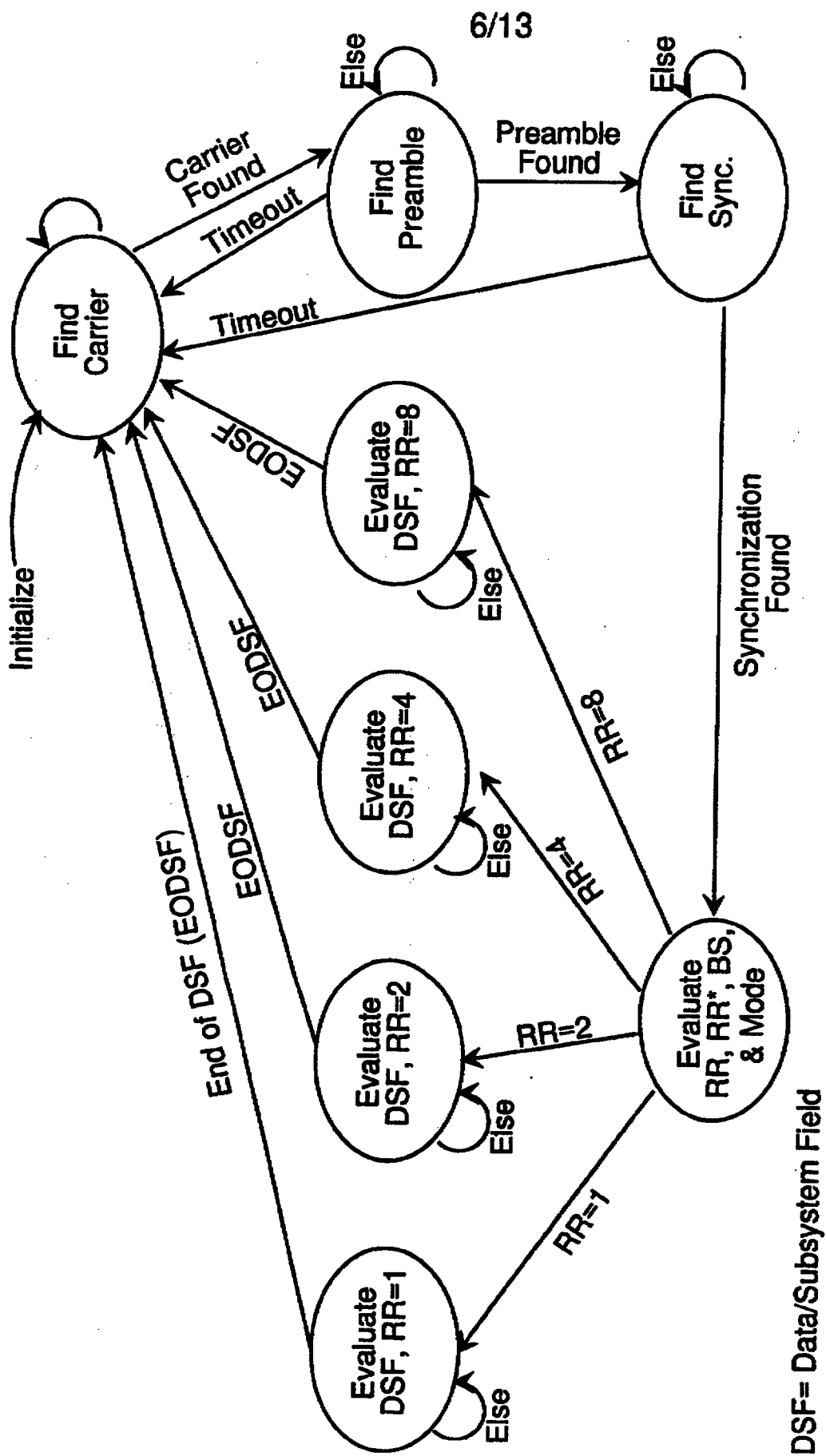


FIG. 7

7/13

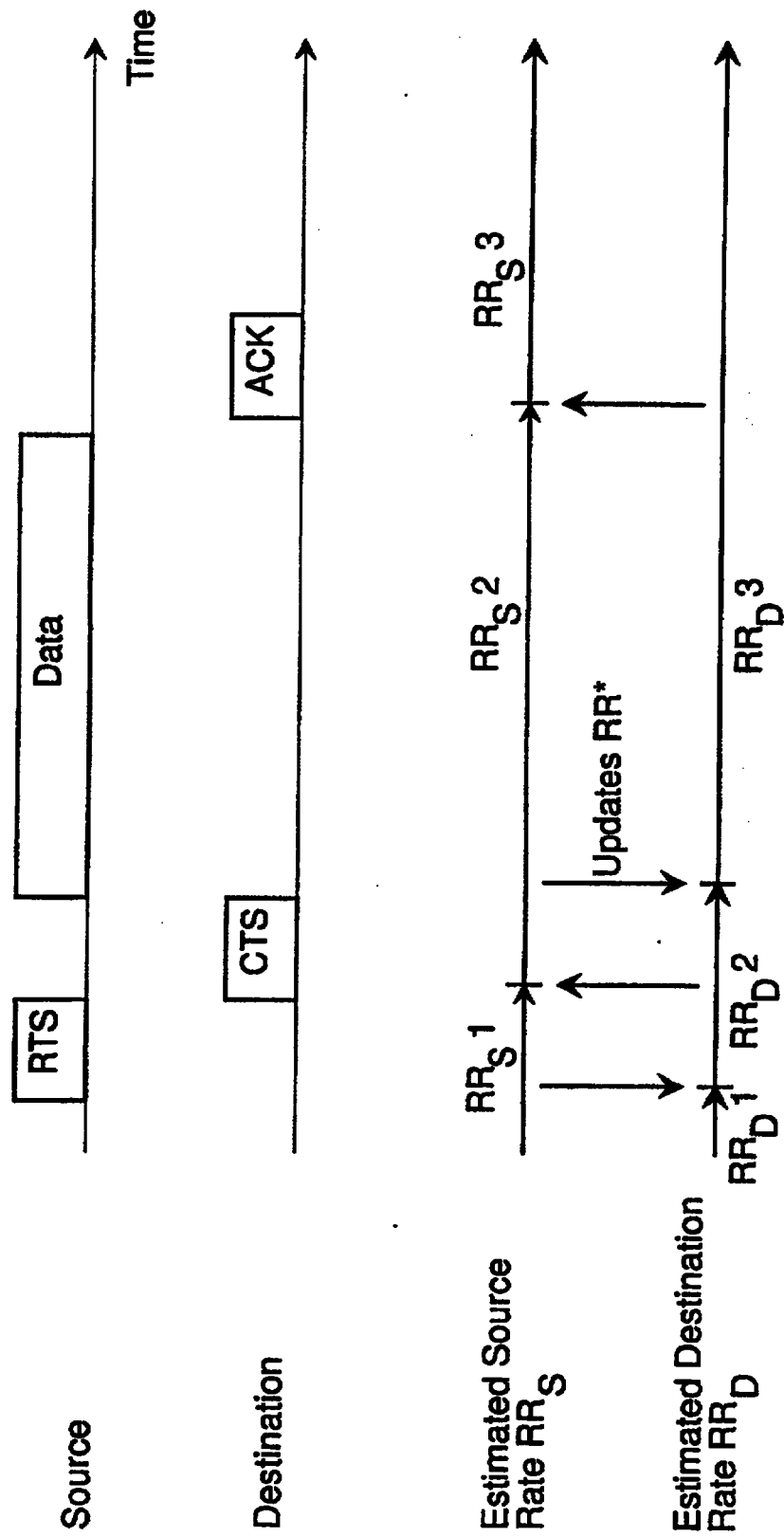


FIG. 8

8/13

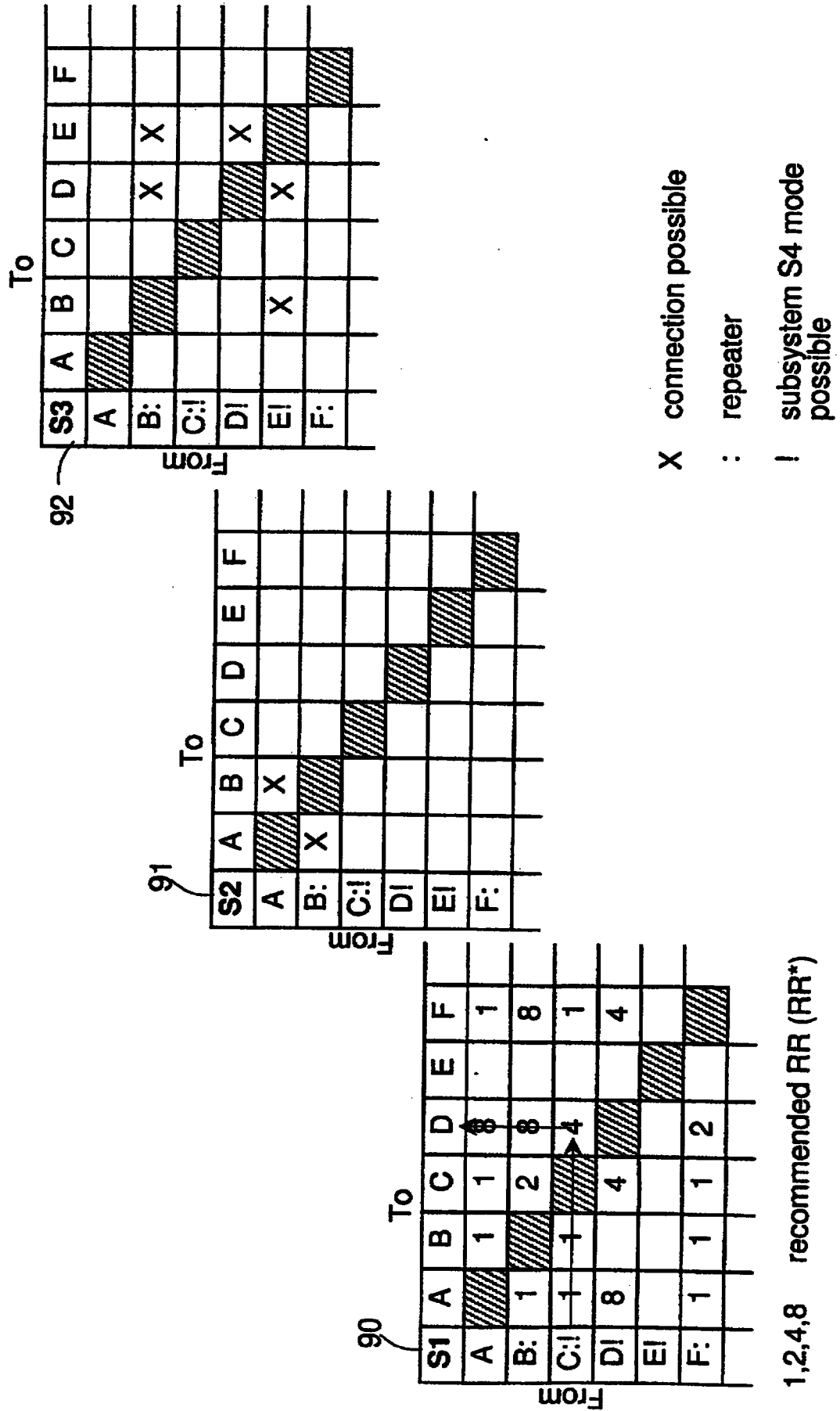


FIG. 9

9/13

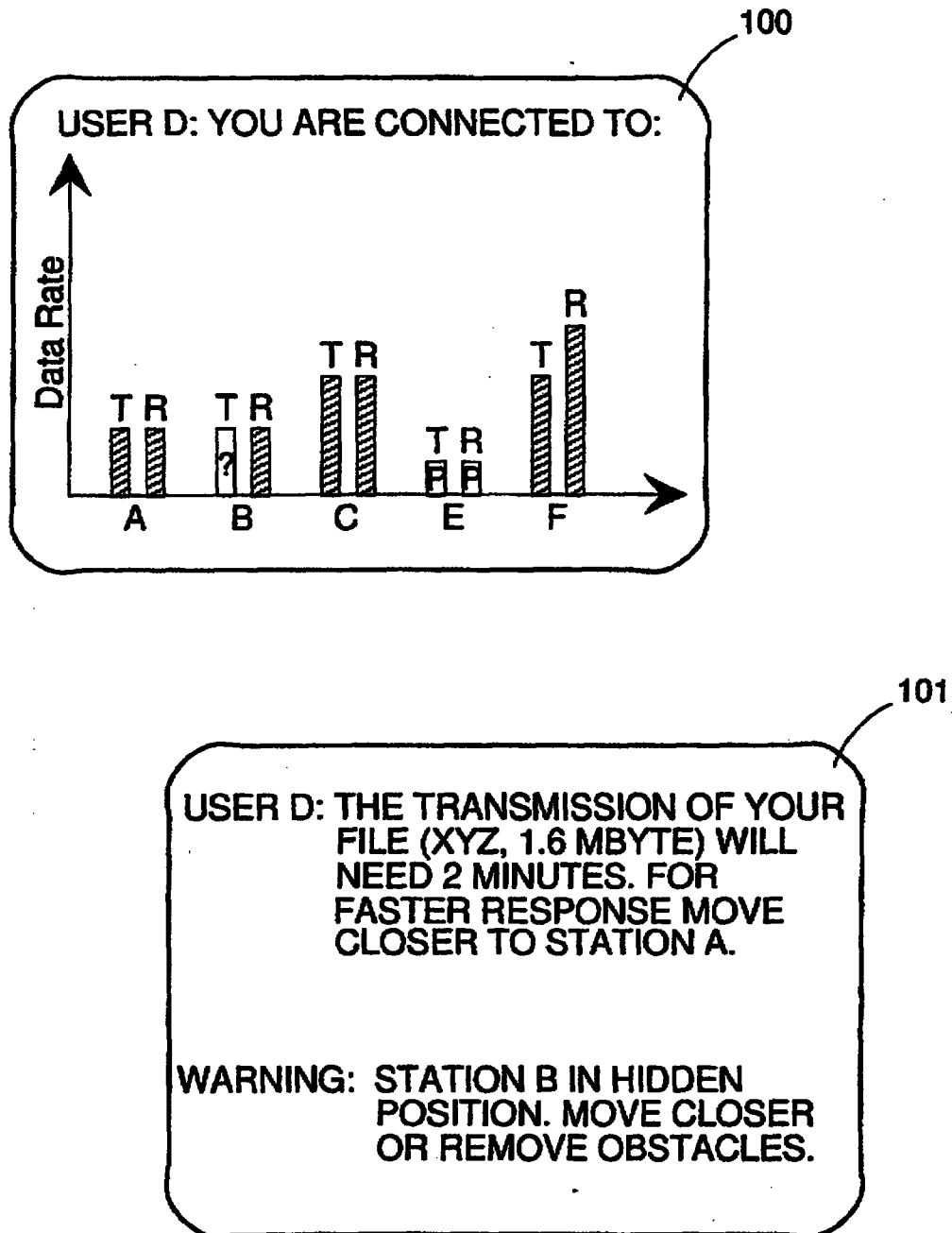


FIG. 10

10/13

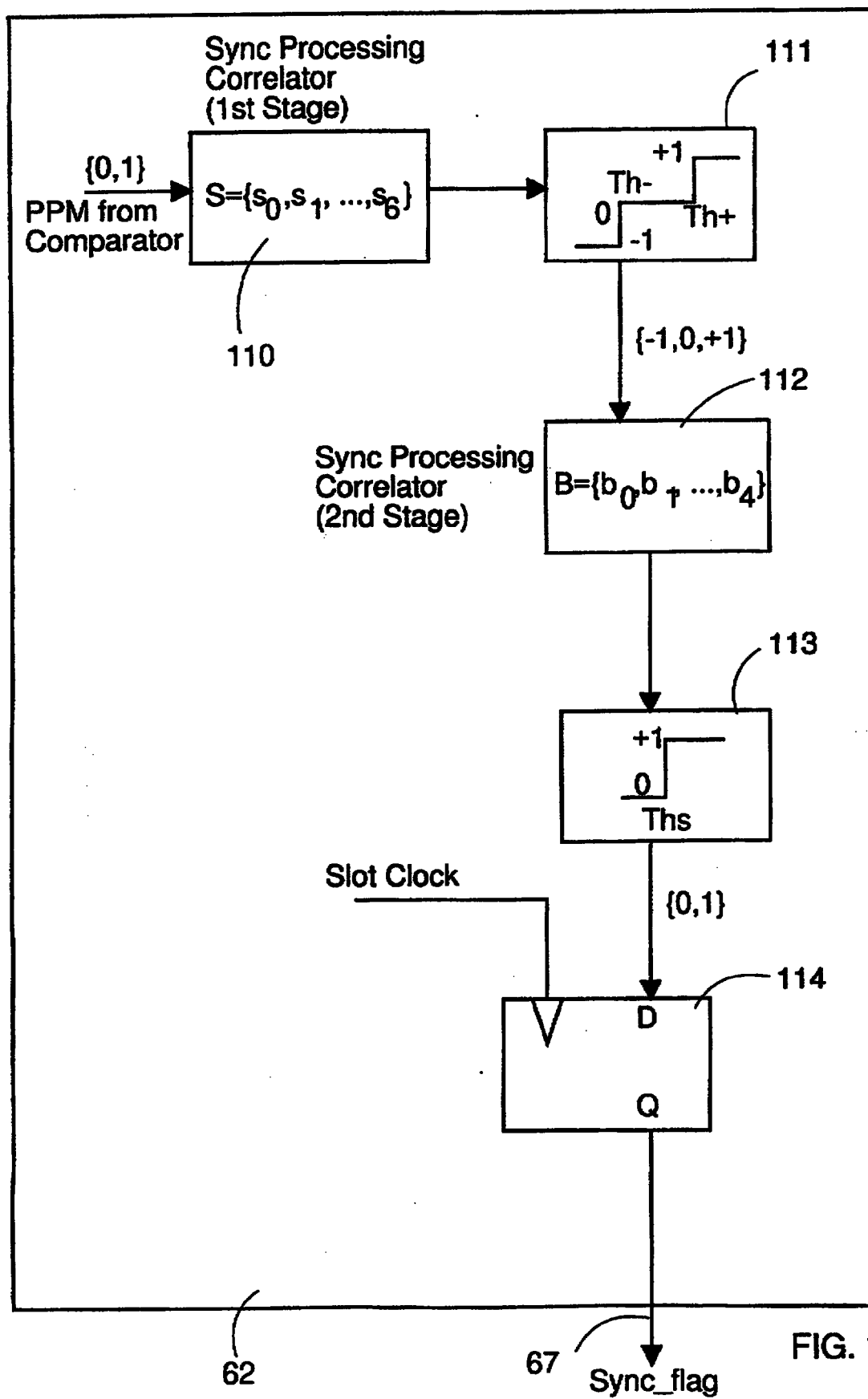


FIG. 11

11/13

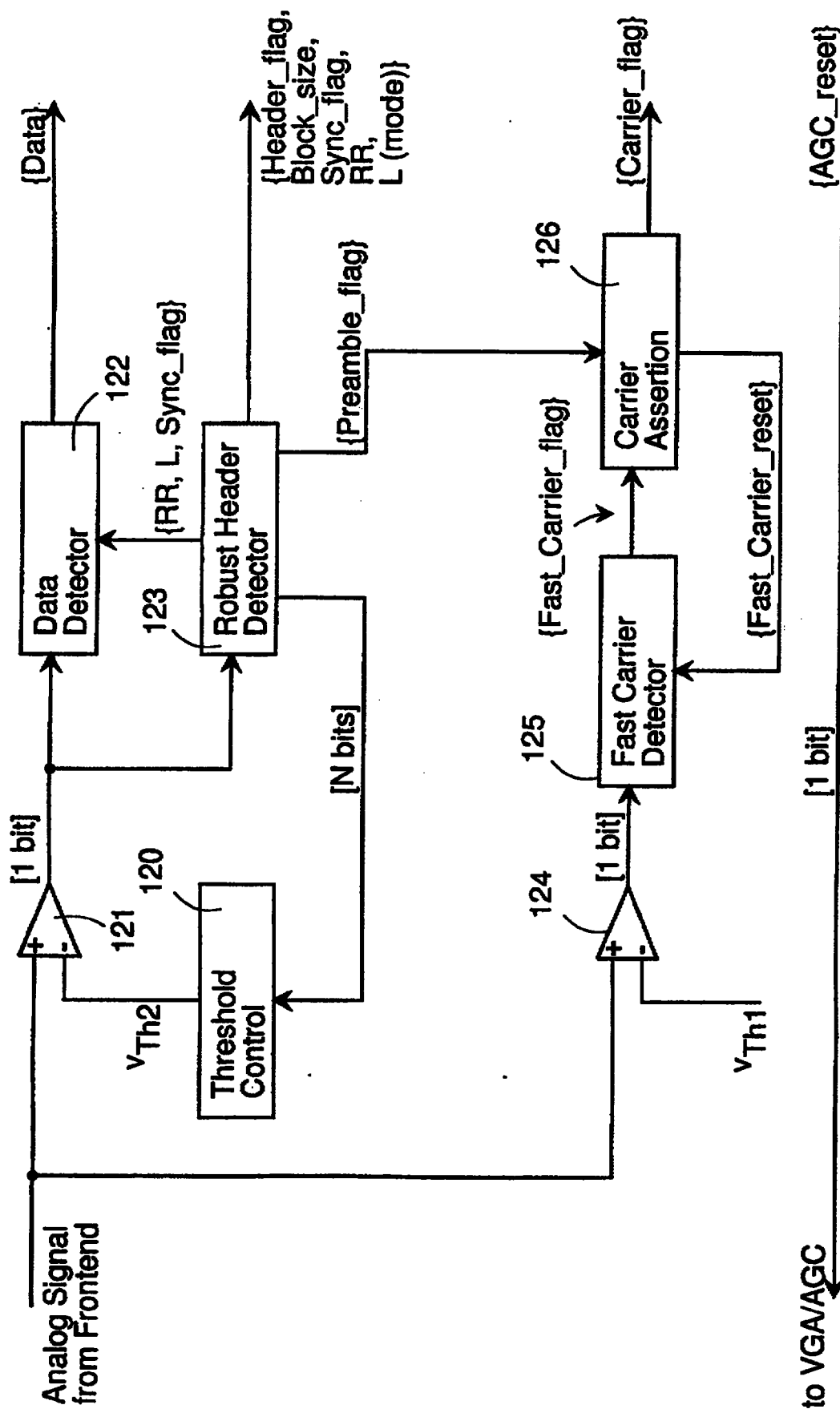


FIG. 12

12/13

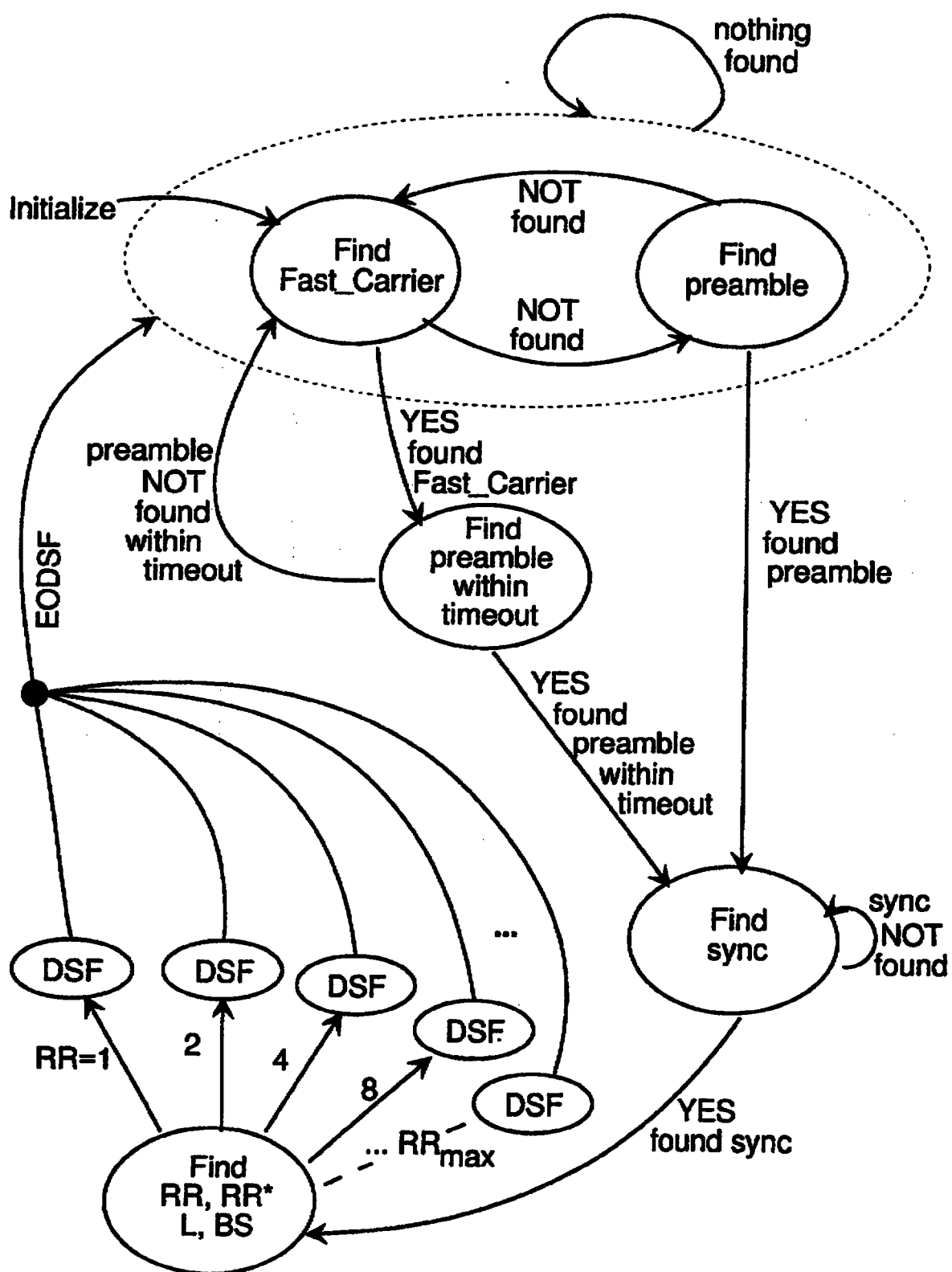
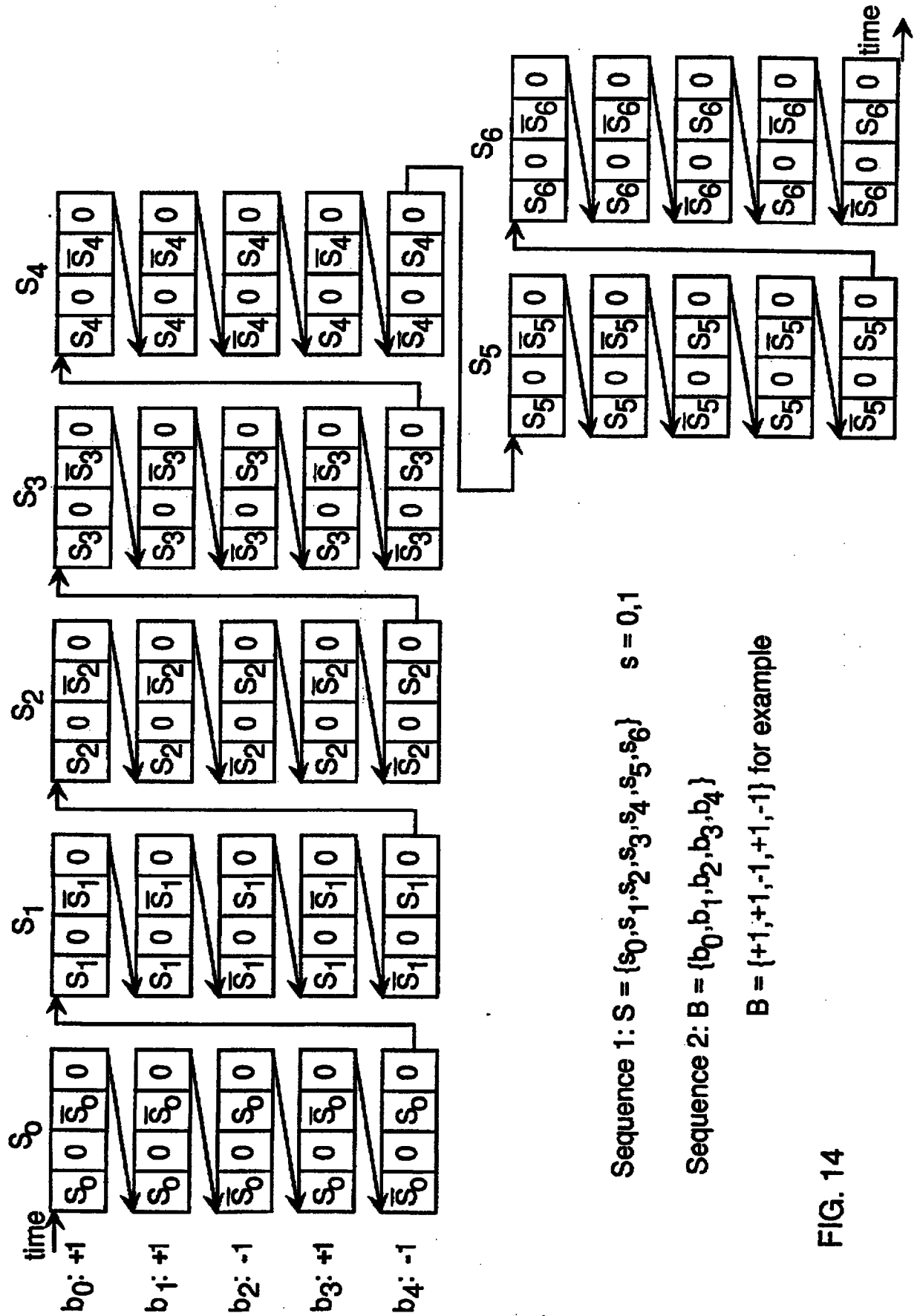


FIG. 13



1 A solution which accommodates the different requirements and needs of
current and future light-based communication systems and ensures their
coexistence and/or compatibility - within a common operating environment
(e.g. within a large area office) - is presently not available.

5 It is thus an object of this invention to provide a wireless optical
communication system which enables multi-mode operation.

It is another object of this invention to provide a method and apparatus for
10 wireless multi-mode optical communication systems.

It is a further object of the present invention to solve typical problems of
current optical communication system, namely channel quality estimation,
frame/symbol synchronization and so forth.

15 It is another object of the present invention to provide a method and
apparatus for wireless multi-mode optical communication systems which
works even under extremely bad channel conditions.

20

SUMMARY OF THE INVENTION

The invention as claimed is intended to meet these objectives. It provides a
method and apparatus enabling wireless optical communication between a
25 transmitting station and a first receiving station capable of receiving data
which are modulated using a first modulation method and a second
receiving station capable of receiving data which are modulated using a
second modulation method. A novel and inventive robust physical layer
header (RPLH) is employed for this purpose. According to the present
30 invention

1. said transmitting station provides a preamble comprising frames
forming a periodic sequence of pulses, i.e., 'a sequence of pulses with



- 1 defined period, the number of slots (L) per frame and the frame content
as such being known to each of said receiving stations,
2. said transmitting station optically transmits said sequence of pulses,
- 5 3. each of said receiving stations performs carrier detection based on said
sequence of pulses received,
4. each of said receiving stations determines said period of the sequence
10 of pulses to obtain relative synchronization,
5. each of said receiving stations adjusts its clock to the phase of the slots
of the received sequence of pulses, and clocks said incoming sequence
of pulses through a shift register,
- 15 6. said transmitting station transmits a unique synchronization word which
is aligned to the period of said preamble,
7. each of said receiving stations correlates said sequence of pulses in
20 said shift register with said unique synchronization word known to it in
order to achieve absolute synchronization with said transmitting station
upon recognition of said synchronization word,
8. said transmitting station now indicates in a control field of predefined
25 length which modulation method will be used in the appended
data/subsystem field, such that said all receiving stations which are able
to support the respective modulation method wait for data to be
transmitted in this data/subsystem field.
- 30 It is to be noted that the sequence of the above steps is not mandatory.
Some of the steps can be also carried out in parallel.

1 Depending on the particular implementation, it is advantageous if the
transmitting station further indicates in said control field the length of the
appended data/subsystem field such that a receiving station can extract said
information to determine the time duration for muting its own transmitter to
5 avoid signal collision with the ongoing transmission (virtual carrier sense).
Under certain circumstances it is also useful to provide other control
information in said control field for communication link and network control.
Furthermore, information may be exchanged to allow negotiation and/or
adaptation of the data rate used for transmission. This allows to optimize
10 the throughput depending on the conditions (quality) on the channel. It is
also of advantage to provide priority-access information which allows
several co-existing pico-cells within one and the same communication cell.

Further advantages of the present invention and additional examples of
15 information which may be exchanged using the inventive robust physical
layer header follow in the detailed description.

The present invention can either be used for communication within a
single-mode system, i.e., for communication between stations supporting the
20 same modulation method, or for communication in a multi-mode system. To
ensure that multi-mode communication is possible, the respective hardware
according to the present invention has to be provided and any
communication has to be initiated according to the above steps.

25

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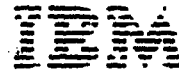
1 In some cases it may be advantageous to transmit access priority
information within the control field 59 which is suited to distinguish
information of a first communication cell from information of a second,
interfering communication cell. Such a measure enables coexistence of
5 different simultaneously active communication cells (pico cells) within a
single cell 40 and each claiming the full ~~channel~~^{7 channel} capacity by ignoring the
virtual carrier sense information contained in the RPLH from other pico
cells. This is possible since the signal strengths within such a pico cell are
sufficiently high to allow channel capturing and thus remain unimpaired by
10 the interference from other distant pico cells. A pico cell may contain two
or more mobile or fixed stations and may also contain a station for access
to wired networks (LANs).

Figure 5 shows a first implementation of the present invention. According
15 to this implementation, the RPLH is generated if payload (binary data), or
information are to be sent over the optical channel 14. The RPLH is
generated by a header generator 10 whereas the binary data are processed
and encoded by a suitable encoder 11 used to map the binary data into
PPM symbols. In addition, a forward error correction system (not shown)
20 may be employed.

In the first implementation, the encoder is a pulse-position modulation
(PPM) encoder 11. A light emitting diode (LED) driver 12 feeds the signals
to be transmitted to a LED 17. The LED driver 12 may have a fanout of up to
25 eight devices, yielding a composite optical peak power of up to 2W, for
example. On the other side of the optical channel 14 there is a photodiode
18 (or an array of photodiodes) which receives the signals from the LED 17.
The output of the photodiode 18 is processed by the receiver's analog
frontend 13, for example comprising an amplifier and automatic gain control
30 (AGC) circuitry. Preferably, the analog frontend 13 should be designed to
prevent latch-up in the presence of high levels of ambient light, and the
AGC circuitry should offer a large dynamic range in excess of 70dB. Ruling
out soft demodulation to avoid the complexity of multi-bit processing, the

1 amplitude controlled analog signal provided by the frontend 13 of the
present embodiment is applied to a threshold device 15 (comparator) which
generates a binary-valued, continuous-time output signal. The output signal
is then processed by means of a digital processing unit 16. The latter at
5 least includes such functions as carrier sensing (carrier detection), slot
timing recovery and relative as well as absolute data symbol
synchronization by analyzing the fields 52 and 53 of the RPLH. Depending
on the information transmitted in the control field 59 of the RPLH, the digital
processing unit 16 may also provide for extraction of user data rate and
10 data block size, data decoding and channel quality estimation. An example
of the receiver's digital processing unit 16 is given and described in
connection with Figure 6.

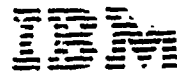
In Figure 6, details of an embodiment of a receiver's digital processing unit
15 16 are shown. Upon receiving a preamble frame ~~7~~ from the comparator 15,
first the slot clock is recovered by means of a first-order, digital
phase-locked loop (PLL) 60 with variable loop gain and preprocessing to
better cope with the noisy PPM signals. Phase estimates and subsequent
phase adjustment are based on n-times ($n=8$, for example) oversampling by
20 means of a slot sampler 61 of the binary-valued signal delivered by the
threshold device 15. The PLL loop gain is controlled by a master state
machine 63 (MSM). The operation of the MSM 63 is illustrated in Figure 7.
Preferably, the gain is set high at the beginning of preamble reception to
obtain fast phase acquisition and to reduce the probability of a hang-up
25 condition of the PLL 60. To prevent the local clock phase from slipping
during tracking of the received signal phase, the loop gain is changed to a
lower value after correct detection of carrier and preamble data by the
carrier sense circuit, according to the present implementation. The PLL 60
locks on the rising edge of the input signal and the recovered slot clock
30 (e.g. 4 MHz) is adequately delayed to serve as reference for the slot
sampler 61. A sampling clock's phase resolution of 45° is sufficient for slot
sampling without performance degradation. The remaining parts of the
circuits are timed with the recovered slot clock (e.g. 4 MHz). Symbol



Revised Set of Claims (8 October 1997)

Claim 1 (amended):

1. Method enabling wireless optical communication between a transmitting station and a first receiving station capable of receiving data which are modulated using a first modulation method and a second receiving station capable of receiving data which are modulated using a second modulation method, whereby
 - a. said transmitting station provides a preamble (52) comprising frames forming a periodic sequence of pulses with defined period, the number of slots (L) per frame and the frame content being known to said receiving stations,
 - b. said transmitting station optically transmits said sequence of pulses,
 - c. said receiving stations perform carrier detection based on said sequence of pulses received,
 - d. each of said receiving stations determines said period of the sequence of pulses to obtain relative synchronization,
 - e. each of said receiving stations adjusts its clock to the phase of the slots of the received sequence of pulses, and clocks said incoming sequence of pulses through a shift register,
 - f. said transmitting station transmits a unique synchronization word (53) aligned to said period, said unique synchronization word (53) being known to said receiving stations,
 - g. each of said receiving stations correlates said sequence of pulses in said shift register with said unique synchronization word known to it in order to achieve absolute synchronization with said transmitting station upon recognition of said synchronization word (53),
 - h. said transmitting station now indicates in a control field (59) of predefined length and structure, [which] whether the first or second modulation method will be used for transmission of the data in a data/subsystem field (51), such that all receiving stations which are



able to support the respective modulation method wait for said data.

Claim 5 (amended):

5. The method of claim 4, whereby said control field (59) comprises a rate reduction field (RR; 54) which indicates to a receiving station how often each pulse-position modulation (PPM) symbol of said data/subsystem field (51) will be repeated.

Claim 7 (amended):

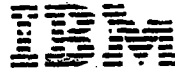
7. The method of claim 6, whereby said recommended rate reduction (RR*) is determined based on pre-defined rules taking into account the actual error rate which occurred during the communication between transmitting station and receiving stations.

Claim 9 (amended):

9. The method of claim 1, whereby said control field (59) comprises a mode field (57) which carries the information used to indicate to said receiving station which modulation method will be used.

Claim 11 (amended):

11. The method of claim 1, whereby said control field (59) comprises information signaling to a receiving station whether said data shall be forwarded by said receiving station (repeater function).



Claim 13 (amended):

13. The method of claim 1 or 4, whereby each of said receiving stations uses an algorithm for recognition of said synchronization word (53) even in the presence of potential errors caused by corrupted optical communication.

Claim 15 (amended):

15. The method of claim 1, whereby a receiving station and/or transmitting station determine the data rate at which said data are to be transmitted.

Claim 16 (amended):

16. The method of claim 1, whereby a receiving station determines a recommended data rate to be used for transmission of said data, taking into account the current quality of the communication channel between transmitting station and receiving station, said recommended data rate being determined based on the knowledge when exactly the control field (59) ends and thus said data/subsystem field (51) starts.

Claim 20 (amended):

20. Multi-mode packet (50, 51) for wireless optical communication between a transmitting station and a first receiving station capable of receiving data which are modulated using a first modulation method and a second receiving station capable of receiving data which are modulated using a second modulation method, said multi-mode packet (50, 51) comprising

- a pulse-position modulated (PPM) data/subsystem field (51) which carries data to be transmitted, and

- a preceding robust physical layer header (RPLH; 50) which can be decoded by all receiving stations, said robust physical layer header (RPLH; 50) comprising:
 - a. a preamble (52) with frames forming a periodic sequence of pulses with defined period, the number of slots per frame and the frame contents being known to said receiving stations,
 - b. a unique synchronization word (53) being known to said receiving stations,
 - c. a control field (59) of predefined length and structure comprising mode information indicating which modulation method is used for the transmission of said data, and a rate reduction field (RR; 54) which indicates to said receiving stations how often each pulse-position modulation (PPM) symbol of said data/subsystem field (51) will be repeated.

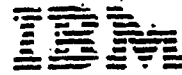
Claim 24 (amended):

24. The multi-mode packet (50, 51) of claim 20, whereby said control field (59) comprises information signaling to a receiving station whether said data shall be forwarded by said receiving station (repeater function).

Claim 27 (amended):

27. Transmitter for wireless optical communication with a first receiving station capable of receiving data which are modulated using a first modulation method and a second receiving station capable of receiving data which are modulated using a second modulation method said communication being initiated using a robust physical layer header (RPLH; 50) which can be decoded by all receiving stations, said transmitter comprising

- a. a header generator providing a preamble (52), being part of said robust physical layer header (RPLH; 50), with frames forming a periodic sequence of pulses with defined period, the number of



slots per frame and the frame content being known to said receiving stations,

- b. means for providing a unique synchronization word (53), being part of said robust physical layer header (RPLH; 50), and being known to said receiving stations,
- c. means for providing a control field (59) of fixed length and known structure, being part of said robust physical layer header (RPLH; 50), said control field (59) indicating the respective modulation method which will be used for transmission of data,
- d. means for modulating said data to be transmitted, and
- e. means for transmitting said sequence of pulses followed by said unique synchronization word (53) being aligned to said sequence of pulses, said control field (59), and said modulated data.

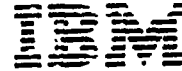
Claim 31 (amended):

31. The transmitter of claim 27, further comprising means for signaling to a receiving station whether said data shall be forwarded by said receiving station (repeater function).

Claim 32 (amended):

32. Receiver for wireless optical communication in a multi-mode communications cell with a transmitting station which transmits

- a robust physical layer header (RPLH; 50) which can be decoded by all receivers in the multi-mode communications cell and which comprises
 - a preamble (52) with frames forming a periodic sequence of pulses with defined period, the number of slots per frame and the frame content being known to said receiver,
 - a unique synchronization word (53) known to the receivers,



- a control field (59) of fixed length and known structure, indicating the respective modulation method which will be used for transmission of data,

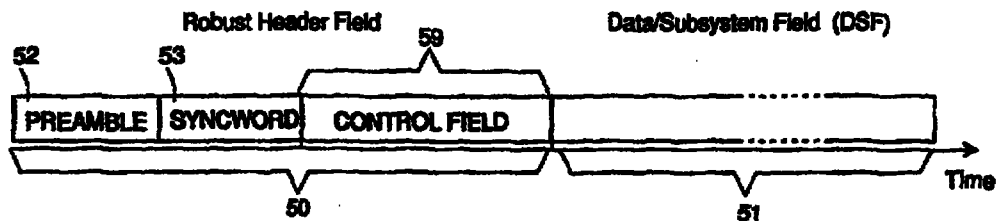
said receiver comprising:

- a. means for determining said period of the sequence of pulses, based on the number of slots per frame and the frame content being known to it, in order to obtain relative synchronization,
- b. means for carrier detection based on said sequence of pulses,
- c. means for adjusting said receiver's clock to the phase of the slots of said sequence of pulses received,
- d. means for clocking said sequence of pulses received through a shift register the length of which is defined by said unique synchronization word (53),
- e. means for correlating said sequence of pulses in said shift register with said unique synchronization word known to it in order to achieve absolute synchronization with said transmitting station upon recognition of said unique synchronization word (53),
- f. means to determine from said control field (59) whether said receiver is able to support the respective modulation method which will be used for the transmission of said data,
- g. means which determine from the information received whether said receiver is the right recipient for said data, and
- h. means enabling said receiver to receive said data right after the end of said control field.

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(21) International Application Number: PCT/IB96/00002 (22) International Filing Date: 3 January 1996 (03.01.96) (71) Applicant (for all designated States except US): INTERNATIONAL BUSINESS MACHINES CORPORATION [US/US]; Old Orchard Road, Armonk, NY 10504 (US). (72) Inventors; and (73) Inventors/Applicants (for US only): De LANGE, Martin [CH/CH]; Klosbachstrasse 43, CH-8032 Zurich (CH). GFELLER, Fritz, Rudolf [CH/CH]; Bahnhofstrasse 78, CH-8803 Rüschlikon (CH). HIRT, Walter [CH/CH]; Hinderweidstrasse 29, CH-8907 Wettswil (CH). (74) Agent: BARTH, Carl, Otto; International Business Machines Corporation, Säumerstrasse 4, CH-8803 Rüschlikon (CH).	(81) Designated States: BR, CA, CN, CZ, HU, JP, KR, PL, RU, SG, US, European patent (AT, BE, CH, DE, DK, ES, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE). Published With international search report.	

(54) Title: **ROBUST METHOD AND APPARATUS ENABLING MULTI-MODE WIRELESS OPTICAL COMMUNICATION**

(57) Abstract

Disclosed is an optical communication system enabling communication between several co-existing transmitting and receiving stations. In order to allow communication between the co-existing stations, a robust physical layer header (RPLH; 50) is employed which can be understood by all participating stations. This robust header (50) at least comprises a preamble (52) consisting of frames forming a periodic sequence of pulses, the number of slots per frame and the frame content being known to all participating stations. The preamble (52) serves for relative synchronization and carrier detection of the receiving stations. The robust header (50) further comprises a unique synchronization word (53) used for absolute synchronization of the receiving stations. This synchronization word (53) is followed by a control field (59) of fixed length and known structure. By means of this control field (59) the receiving stations are informed which modulation method will be used for the transmission of data. Under certain circumstances it is also useful to provide other control information in said control field (59) for communication link and network control. Furthermore, information may be exchanged to allow negotiation and/or adaptation of the data rate used for transmission. This allows to optimize the throughput depending on the conditions (quality) on the channel.