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(54) **SYSTEM, METHOD AND ARTICLE FOR ADAPTIVE FRAMING FOR TDMA MAC PROTOCOLS**

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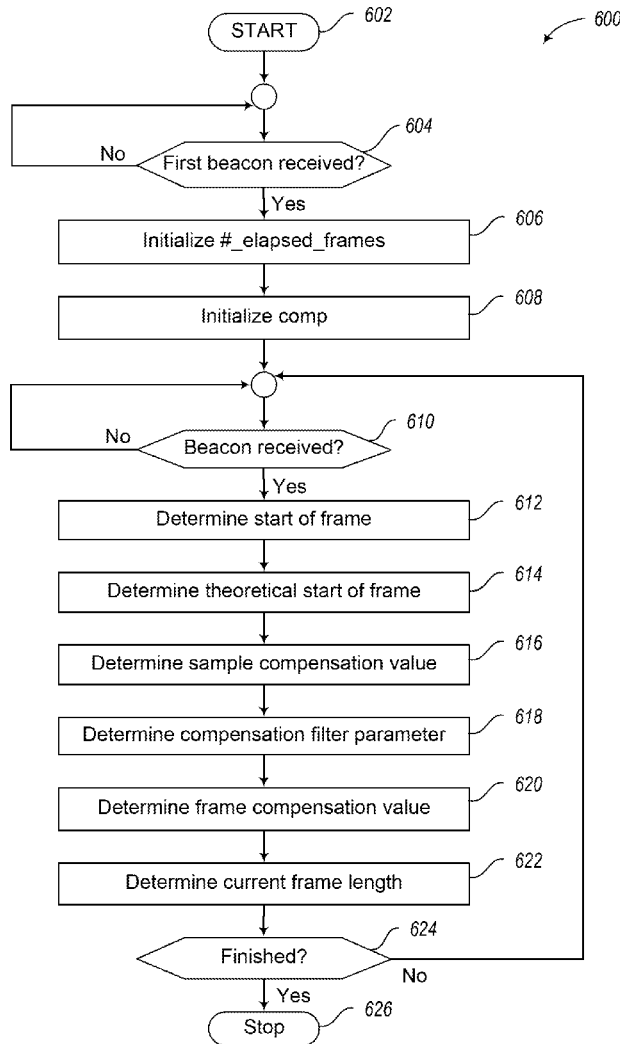
(57) **ABSTRACT**

A device includes an interface and Time Division Multiple Access (TDMA) Medium Access Control (MAC) circuitry coupled to the interface. The TDMA MAC circuitry detects a beacon in a frame having a defined frame duration and determines a frame compensation value based on a start time of the frame, a reference start time of the frame, and a number of elapsed frames. A current frame duration value is determined based on the frame compensation value and the defined frame duration.

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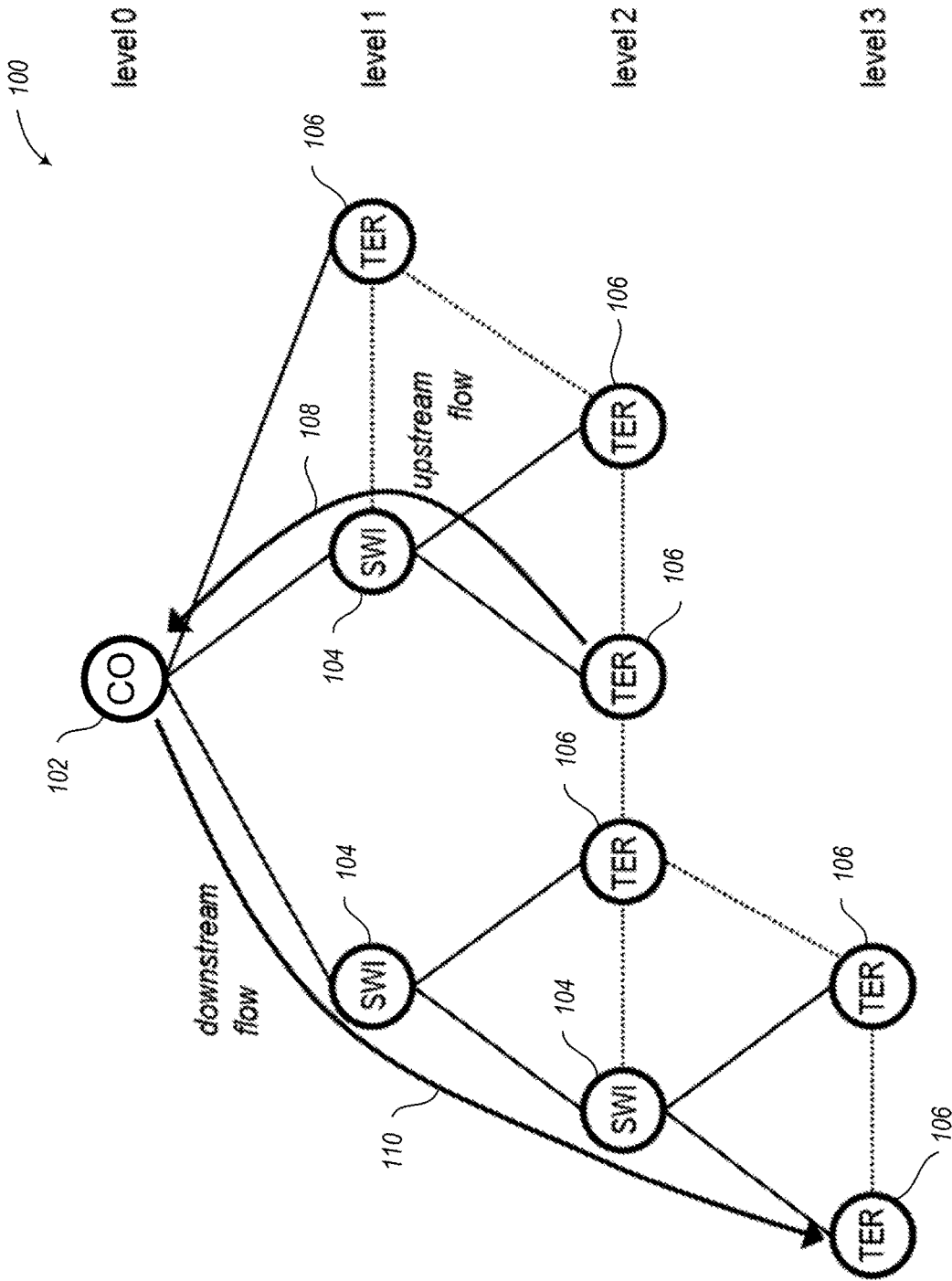


FIG. 1

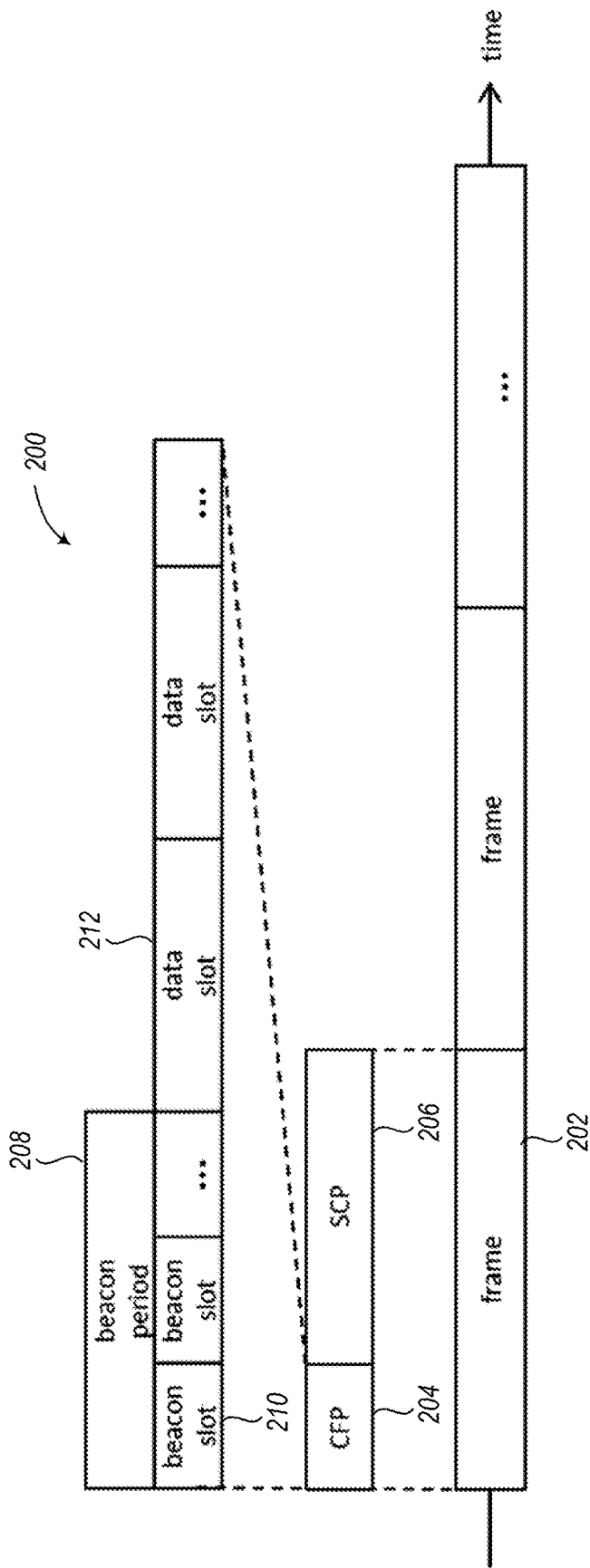


FIG. 2

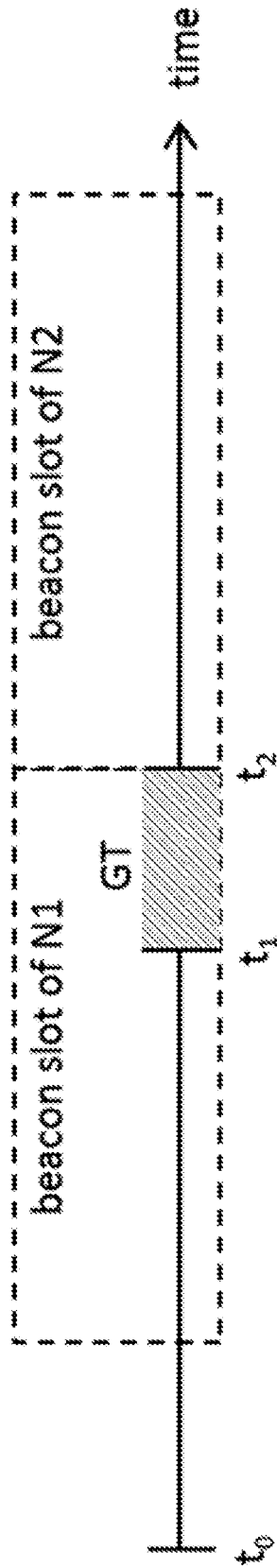


FIG. 3

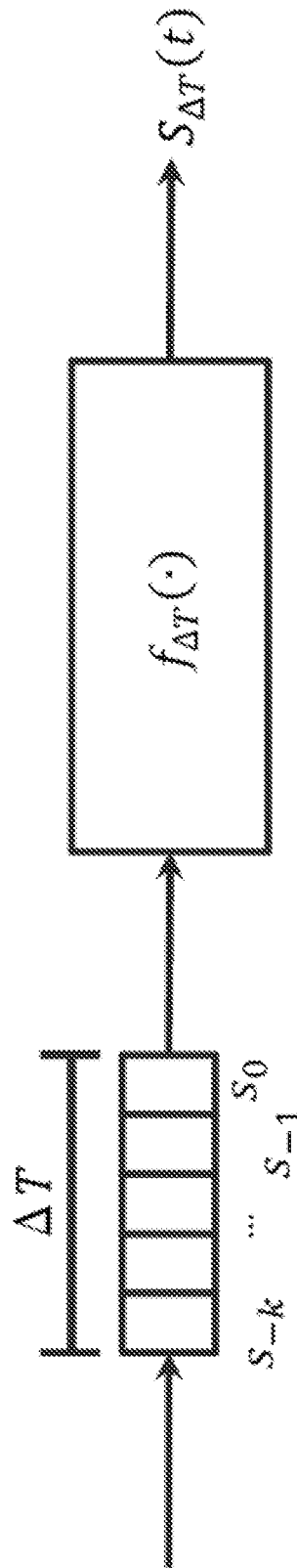


FIG. 4

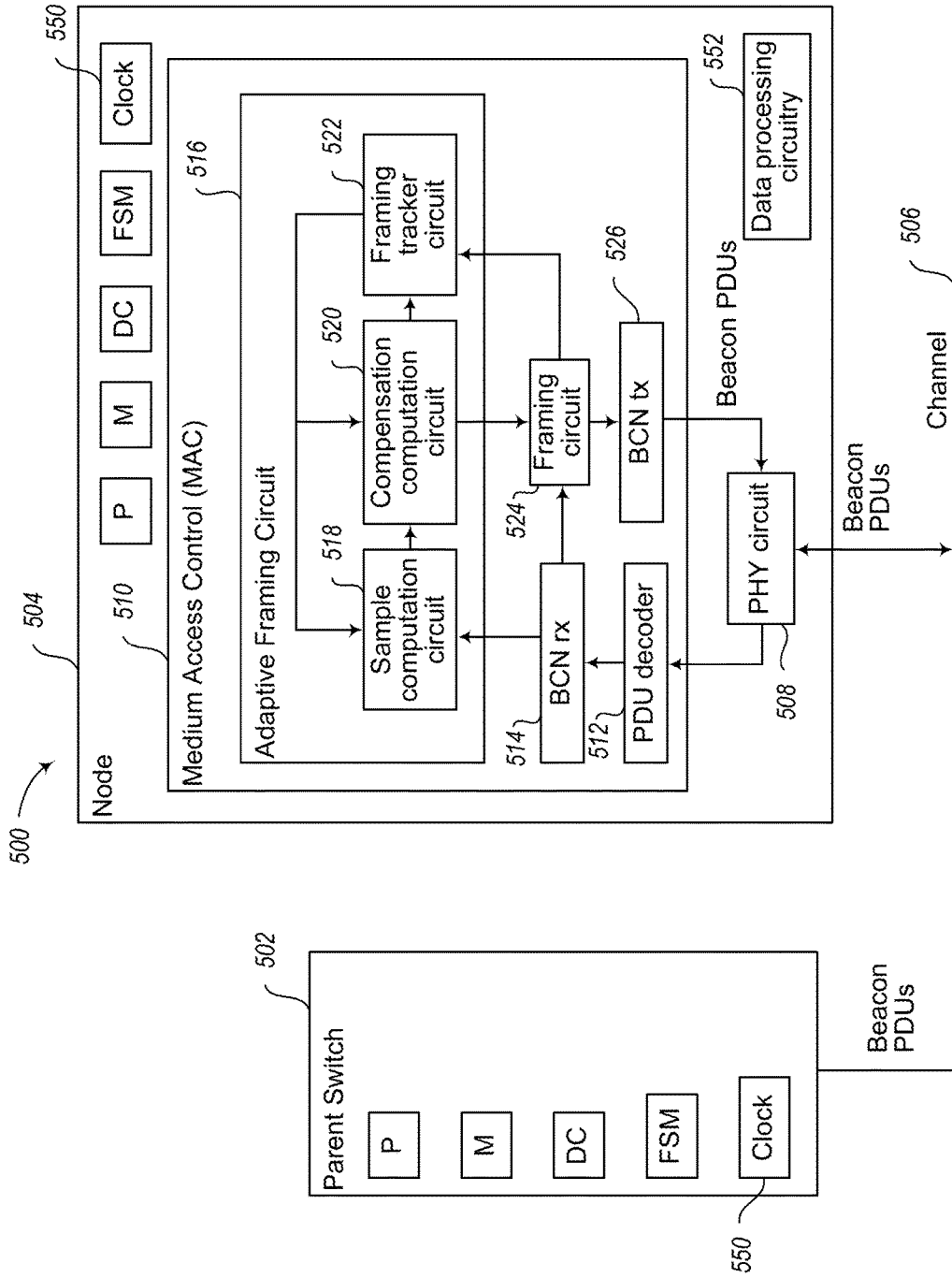


FIG. 5

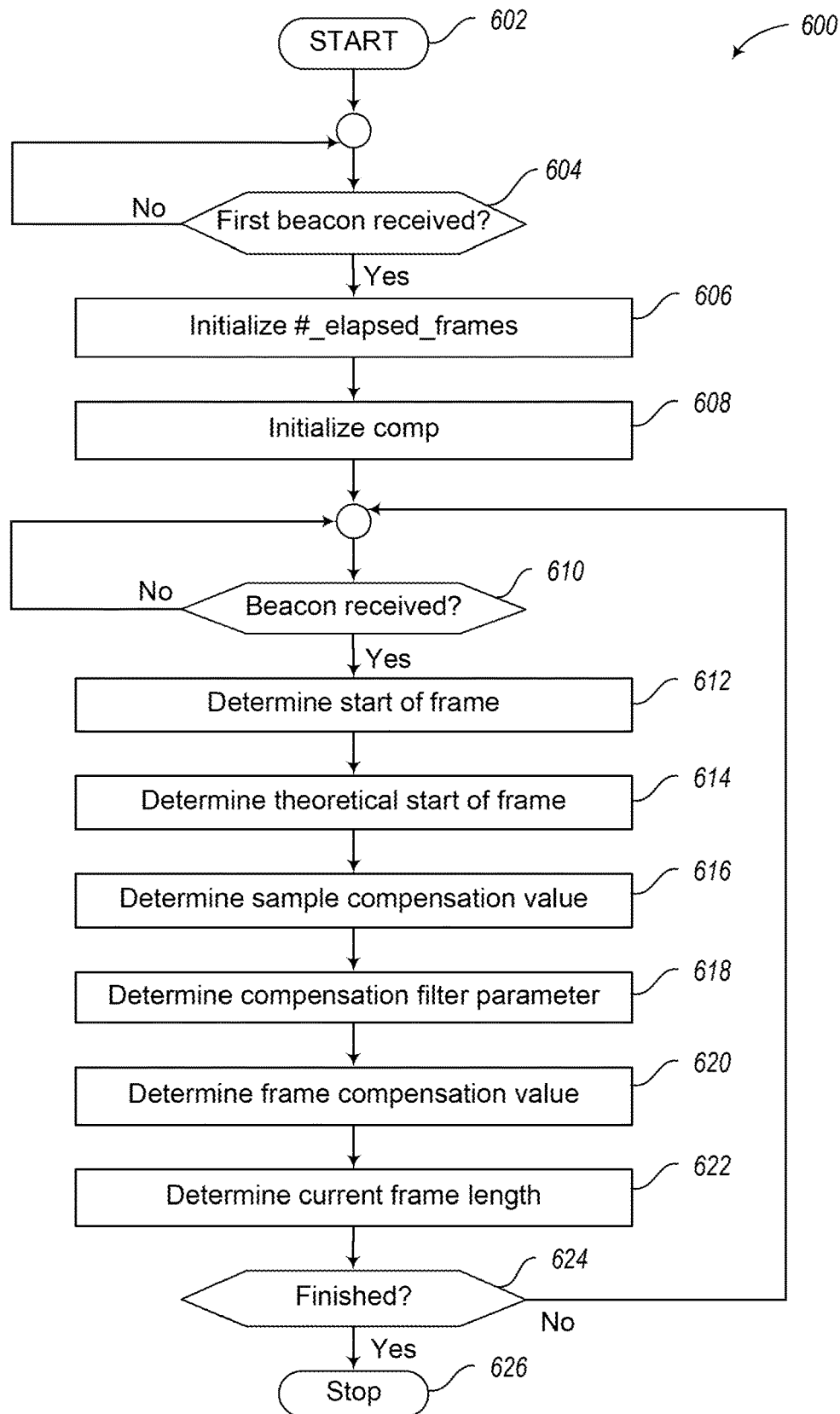


FIG. 6

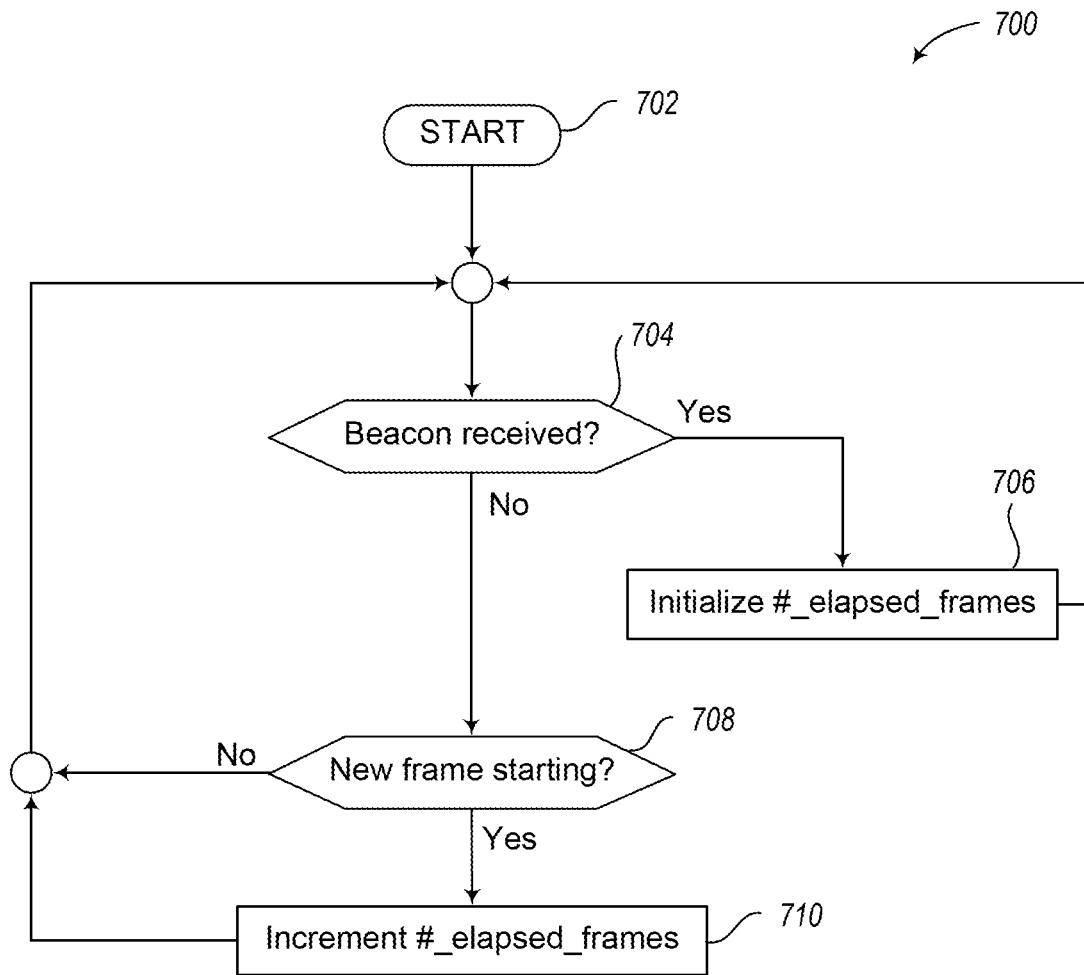


FIG. 7

SYSTEM, METHOD AND ARTICLE FOR ADAPTIVE FRAMING FOR TDMA MAC PROTOCOLS

BACKGROUND

Technical Field

[0001] The present description relates to systems, methods and articles for adaptive framing for Time-Division Multiple Access (TDMA) Medium Access Control (MAC) protocols, either wired or wireless, single or multi hops.

Description of the Related Art

[0002] Time-Division Multiple Access (TDMA) Medium Access Control (MAC) protocols may be employed in wired or wireless networks, and may be configured as single or multi hops networks.

[0003] For example, powerline networks are wired networks having data packets which travel on cables used to transport electricity. Generally, powerline networks may be classified into two classes: indoor networks, which typically implement local area networks (LANs), usually at high bit rates for content distribution within, for example, a house; and outdoor networks, which typically implement wide area networks (WANs), usually at lower bit rates than LAN powerline networks, to transport application data related to power consumption and usage.

[0004] A power distribution grid coupled with a powerline WAN may be referred to as a smart grid. A smart grid may use the data transmitted to, for example, improve the efficiency of power generation and distribution, automatic meter reading (AMR), etc. In AMR, a low bit rate application is typically employed in which a central data aggregator periodically requests remote meters to report the power consumed until that moment. Communication protocols have been defined to support WANs, including protocols supporting powerline WANS such as PowerLine Intelligent Metering Evolution (PRIME) networks, G3 and Meters and More protocols.

BRIEF SUMMARY

[0005] In an embodiment, a device comprises: an interface, which, in operation, receives a data stream of a network; and Time Division Multiple Access (TDMA) Medium Access Control (MAC) circuitry, coupled to the interface, wherein the TDMA MAC circuitry, in operation: detects a beacon packet in a frame of the data stream, wherein a frame is a period of time having a defined frame duration; determines a frame compensation value based on a start time of the frame, a reference start time of the frame, and a number of elapsed frames; and determines a current frame duration value based on the determined frame compensation value and the defined frame duration. In an embodiment, the TDMA MAC circuitry, in operation, determines the frame compensation value by applying a filter based on the number of elapsed frames. In an embodiment, the TDMA MAC circuitry, in operation, selects a filter parameter based on the number of elapsed frames. In an embodiment, the TDMA MAC circuitry, in operation, determines a sample compensation value based on the start time of the frame, the reference start time and the number of elapsed frames and determines the frame compensation value by applying the filter to the sample compensation

value. In an embodiment, the TDMA MAC circuitry, in operation: determines the reference start time of the frame based on a start time of a previous frame in which a beacon was detected, the defined frame duration and the number of elapsed frames. In an embodiment, the number of elapsed frames is a number of frames elapsed since a frame in which a previous beacon was detected. In an embodiment, the TDMA MAC circuitry, in operation, controls transmission of a beacon at a transmission time based on the current frame duration value. In an embodiment, the beacon is transmitted by a switch node or a coordinator of the network.

[0006] In an embodiment, a method comprises: detecting, by a node of a Time Division Multiple Access (TDMA) network, a beacon transmitted in a frame, wherein a frame is a period of time having a defined frame duration; determining, by the node, a frame compensation value based on a start time of the frame, a reference start time of the frame, and a number of elapsed frames; and determining, by the node, a current frame duration value based on the frame compensation value and the defined frame duration. In an embodiment, the method comprises determining the frame compensation value by applying a filter based on the number of elapsed frames. In an embodiment, the method comprises selecting a filter parameter based on the number of elapsed frames. In an embodiment, the method comprises: determining a sample compensation value based on the start time of the frame, the reference start time, and the number of elapsed frames; and applying the filter to the sample compensation value. In an embodiment, the method comprises determining the reference start time of the frame based on a start time of a previous frame in which a beacon was detected, the defined frame duration and the number of elapsed frames. In an embodiment, the number of elapsed frames is a number of frames elapsed since a frame in which a previous beacon was detected. In an embodiment, the method comprises controlling, by the node, a transmission time of a beacon based on the current frame duration value. In an embodiment, the beacon is transmitted by a switch node or a coordinator of the TDMA network.

[0007] In an embodiment, a system, comprises: node data processing circuitry, which, in operation, generates data related to a node; and Time Division Multiple Access (TDMA) Medium Access Control (MAC) circuitry, coupled to the node circuitry, wherein the TDMA MAC circuitry, in operation: detects a beacon in a TDMA frame, wherein a frame is a period of time having a defined frame duration; determines a frame compensation value based on a start time of the frame, a reference start time of the frame, and a number of elapsed frames; and determines a current frame duration value based on the frame compensation value and the defined frame duration. In an embodiment, the TDMA MAC circuitry, in operation, determines the frame compensation value by applying a filter based on the number of elapsed frames. In an embodiment, the TDMA MAC circuitry, in operation, controls transmission of a beacon at a transmission time based on the current frame duration value. In an embodiment, the system comprises an integrated circuit including the TDMA MAC circuitry. In an embodiment, the integrated circuit includes the node data processing circuitry. In an embodiment, the TDMA MAC circuitry, in operation, implements a PowerLine Intelligent Metering Evolution (PRIME) network protocol.

[0008] In an embodiment, a non-transitory computer-readable medium has contents which cause a node of a Time

Division Multiple Access (TDMA) network to perform a method, the method comprising: detecting a beacon in a frame, wherein a frame is a period of time having a defined frame duration; determining a frame compensation value based on a start time of the frame, a reference start time of the frame, and a number of elapsed frames; and determining a current frame duration value based on the frame compensation value and the defined frame duration. In an embodiment, the contents comprise instructions executed by processing circuitry of the node. In an embodiment, the method comprises controlling a transmission time of a beacon by the node based on the current frame duration value.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

[0009] FIG. 1 is a functional block diagram of time division multiple access (TDMA) network according to an embodiment.

[0010] FIG. 2 illustrates a generic structure of frames of a TDMA network according to an embodiment.

[0011] FIG. 3 illustrates guard times separating consecutive beacons.

[0012] FIG. 4 illustrates an embodiment of a method of an adaptive framing.

[0013] FIG. 5 illustrates an embodiment of a network having a node employing an embodiment of an adaptive frame algorithm.

[0014] FIG. 6 illustrates an embodiment of a method of adaptive framing.

[0015] FIG. 7 illustrates an embodiment of a method of tracking a number of elapsed frames.

DETAILED DESCRIPTION

[0016] In the following description, certain details are set forth in order to provide a thorough understanding of various embodiments of devices, systems, methods and articles. However, one of skill in the art will understand that other embodiments may be practiced without these details. In other instances, well-known structures and methods associated with, for example, switches, computing systems, communication networks, etc., have not been shown or described in detail in some figures to avoid unnecessarily obscuring descriptions of the embodiments.

[0017] Unless the context requires otherwise, throughout the specification and claims which follow, the word “comprise” and variations thereof, such as “comprising,” and “comprises,” are to be construed in an open, inclusive sense, that is, as “including, but not limited to.”

[0018] Reference throughout this specification to “one embodiment,” or “an embodiment” means that a particular feature, structure or characteristic described in connection with the embodiment is included in at least one embodiment. Thus, the appearances of the phrases “in one embodiment,” or “in an embodiment” in various places throughout this specification are not necessarily referring to the same embodiment, or to all embodiments. Furthermore, the particular features, structures, or characteristics may be combined in any suitable manner in one or more embodiments to obtain further embodiments.

[0019] The headings are provided for convenience only, and do not interpret the scope or meaning of this disclosure.

[0020] The sizes and relative positions of elements in the drawings are not necessarily drawn to scale. For example,

the shapes of various elements and angles are not necessarily drawn to scale, and some of these elements may be enlarged and positioned to improve drawing legibility. Further, the particular shapes of the elements as drawn are not necessarily intended to convey any information regarding the actual shape of particular elements, and have been selected solely for ease of recognition in the drawings.

[0021] An embodiment of an adaptive framing method is described with reference to a TDMA network, either wired or wireless, where nodes are logically organized in a tree shaped hierarchy.

[0022] In a tree-shaped network, every node has a single parent (switch) through which the node can communicate with other nodes within the network. The network is traversed by chains (tree branches) of such switches that together form the network backbone. Data and control packets flow through the tree branches from sources to destinations. Generally, data and control packets travel from source nodes to the tree’s root node (coordinator) and from the tree’s root node to destination nodes in the tree. In some configurations, the root node is replaced by the first switch in the path common to both source and destination. In such a network, nodes are logically organized as a hierarchical tree. In a particular configuration of an embodiment, such a tree may collapse into a star, with all nodes receiving beacons from just another node.

[0023] Generally, every switch (including the root node, which is also a switch) provides time synchronization to child nodes of the switch. A switch receives time synchronization from the switch’s parent switch and forwards the time synchronization to the switch’s child nodes. Such synchronization usually relies on device node internal clocks. Packets exchanged are used to align clocks, which are then used by device nodes to keep track of time. Clocks, however, are not perfect and synchronization may be lost from time-to-time. For that reason, usually some countermeasures are put in place to avoid clocks drifting too much. If not so, network synchronization may be lost. The loss of network synchronization leads to instability and network performance degradation.

[0024] An embodiment of a synchronization method facilitates providing a robust time synchronization procedure for a network employing a TDMA MAC protocol. An embodiment facilitates avoiding the need to implement more complex countermeasures. In an embodiment, a receiver-method is employed which facilitates each receiver node maintaining time synchronization with the synchronization of the node’s parent. In an embodiment, the method is compliant with any TDMA MAC protocol of the network. Providing a robust time synchronization procedure increases network stability. In an embodiment, a robust time synchronization may be implemented using software, which may reduce the cost of implementation of an embodiment. Embodiments may be employed in single-hop networks (e.g., star-shaped mentioned above), or multi-hop networks (e.g., tree-shaped mentioned above), and both types of networks may benefit from a more robust time synchronization procedure. In an embodiment, improvement in synchronization is facilitated without employing specific synchronization information exchanges in addition to beacons.

[0025] For example, PRIME is a protocol operating at a data link layer of an International Organization for Standardization/Open Systems Interconnection (ISO/OSI) stack architecture and provides multi-hop power-line communi-

cation over a self-organizing packet-switched network of Service Nodes (SN) controlled by a central Base Node (BN). Two versions of PRIME are currently employed, version 1.3.6 and a newer version 1.4. While the versions differ in various aspects, the MAC sub-layers of both versions of PRIME have a network-wide Time Division Multiple Access (TDMA) policy, and a tree-shaped organization. An embodiment facilitates addressing time-synchronization control issues that may arise, for example, from these characteristics of the PRIME protocols.

[0026] The TDMA class of MAC protocols assumes that: all nodes in the network share a knowledge of time; time is divided in intervals of a known or knowable length, often called frames; and nodes have access to the transmission medium at determined time slots within a frame.

[0027] Time division control information that helps nodes to establish how and when to access the transmission medium, such as the structure of a frame, time information, etc., may be communicated to nodes in various ways under TDMA protocols. For example, a signal external to the network (e.g., an external pilot signal such as a Global Positioning Signal (GPS) pilot signal) may be employed. In another example, a device within the network may send out-of-band signals or special packets to provide the time division information. Various combinations of signals may be employed.

[0028] In TDMA networks here addressed, the tree root node periodically broadcasts beacons. Each beacon packet reports the structure of a frame and other time information that help receiving nodes to establish when and how to access the transmission medium to receive from or transmit to other nodes.

[0029] TDMA protocols are generally designed to manage transmissions in one-hop networks (star-shaped said above), where all nodes can receive packets from and send packets to a central coordinator. But to facilitate covering long distance among nodes or to allow far away nodes to join the network (when for instance nodes are fixed and hence cannot be moved), TDMA protocols may be configured to support multi-hop, tree-shaped networks.

[0030] In TDMA networks, the coordinator transmits beacons with a fixed frequency, typically one beacon per frame. Nodes directly attached to the coordinator receive its beacons and register with it as “terminals”. Further, nodes directly connected to terminals do not hear the coordinator’s beacons, but may announce their presence to terminals connected to the coordinator. The terminals directly connected to coordinator may request to be promoted to switches. Once a terminal has been promoted to a switch by the coordinator, the switch starts transmitting its own beacons. New terminals may attach themselves to the child nodes of the said switches, and the process may repeat, forming a switch at N-hops distance from the coordinator, with N greater than 1.

[0031] FIG. 1 illustrates an example network **100**. At level 0, there is a single coordinator **CO 102**. At level 1 are devices directly connected to the coordinator **CO 102**. As illustrated, there are two switches **SWI 104** and one terminal **TER 106** connected to the coordinator **102** of the network **100** at level 1. At level 2 are devices directly connected to one of the switches **SWI 104** at level 1. As illustrated, one switch **SWI 104** and three terminals **TER 106** are connected to the network **100** at level 2. At level 3 are devices directly connected to the switch **SWI 104** at level 2. As illustrated,

two terminals **TER 106** are connected to the network **100** at level 3. The network **100** of FIG. 1 has a tree-shaped hierarchy of nodes. The coordinator **CO 102** is the root node, switches **SWI 104** are the intermediate nodes and terminals **TER 106** are the leaves. As illustrated in FIG. 1, solid lines represent branches of the tree and dotted lines represent other links between nodes. Examples of data and control packets flows are illustrated, including a flow upstream from terminals **TER 106** and switch nodes **SWI 104** to the coordinator **CO 102** on multi-hop paths formed by branches of the tree, for example on upstream path **108**, and a flow downstream from the coordinator **CO 102** to switch nodes **SWI 104** and terminals **106** on multi-hop paths formed by branches of the tree, for example on downstream path **110**. The hop-wise distance of a switch node **SWI 104** to the coordinator **CO 102** is the level of a switch, assuming the coordinator **CO 102** is at level 0.

[0032] The source of the network-wide synchronization is the coordinator **CO 102**, which periodically sends beacons. The beacons inform directly attached nodes (e.g., nodes at level 1), about the start and end time of the current frame and the structure of the current frame. FIG. 2 illustrates an example embodiment of a sequence of frames **200**. As illustrated in FIG. 2, the frame sequence **200** comprises a plurality of frames **202**. Each frame **202** is divided into two sub-periods in which packets of defined packet types may be transmitted or defined protocol operations may be performed, a contention free period **204** and a shared contention period **206**.

[0033] The contention free period **204** is dedicated to transmissions explicitly authorized by the coordinator and which source and time duration is known by every node which may be potentially interested in it, so that just one node transmits in that time period and the likelihood that a packet is correctly received is increased. Generally speaking, in the contention free period **204** a beacon period **208** may be reserved and divided into multiple beacon slots **210**, where beacons may be transmitted by either the coordinator (see coordinator **CO 102** of FIG. 1) or switches (see switches **SWI 104** in FIG. 1). Without lack of generality, the beacon period **208** in other TDMA MAC protocols may be distinguished from the contention free period **204** in the frame **202**.

[0034] The shared contention period **SCP 206** may typically be used for transmission of data and control packets according to a carrier sense multiple access (CSMA) scheme, which regulates potentially concurrent transmissions of multiple nodes contending for the use of the transmission medium. In practice, CSMA schemes may reduce the risk of destructive interference between overlapping transmissions, but do not eliminate the risk of interference.

[0035] The beacon transmitted by the coordinator **CO 102** typically indicates the frame structure in terms of beacon slots **210** and data slots **212** and timings to the various nodes of the network. To distribute the information throughout the network, each switch **104** repeats the beacon received from a parent switch in a beacon slot **210** assigned to the switch **104** by the coordinator **102** according to a transmission schedule set by the coordinator **102** (e.g., every eighth frame). To facilitate avoiding collisions and network instability issues, the coordinator **102** assigns different beacon slots to switches which are directly connected to each other (which may thus hear each other’s beacons), and the beacon

slots **210** do not overlap. When collisions occur, a node does not receive a beacon from its parent. Occasional beacons lost do not typically result in network instability (a node can miss an occasional beacon), however, if collisions are frequent such that a node misses several beacons (e.g. if coordinator badly allocates beacons from different switches or switches which have lost synchronization misallocate their beacons, hence making them overlap to those being transmitted by other switches in nearby slots), the node may ultimately become disconnected from the network. If the node is a switch, the entire subtree below the switch may become disconnected from the network.

[0036] To virtually increase the room allocated to beacons, switches may be instructed to send beacons at a lower frequency than one beacon per frame. In some embodiments, the frequency may be as low as once per super-frame (e.g., once every 32 frames in some protocols). This allows beacon slots to be assigned to multiple switches which are not transmitting in the same frame. Beacon slots also may be assigned to multiple switches which are not directly connected to each other.

[0037] Each network device, such as a switch **104** in the network **100**, typically has an internal clock (see FIG. 5). Each switch relies on beacons received from its parent switch and the switch's internal clock to determine the timing of placement of packets on the channel in accordance with the instructions received from the coordinator, and thus to determine the placement of the beacons the switch transmits onto the channel. The beacons are placed at the beginning of the assigned slot or as close as possible to the beginning of the assigned slot. A switch keeps track of the time elapsed since the beginning of a frame using its internal clock to place the switch's beacon in an assigned slot.

[0038] In addition, clock skew, which is the difference in time shown by the clocks of different nodes of a network, can be a significant problem in time-dependent networks like TDMA networks. Moreover, clock errors in different devices of a network are usually different, and the impact of errors in a tree branch may be cumulative. For example, a switch several hops from the coordinator may be significantly out-of-synchronization with the timing of the coordinator.

[0039] Thus, the accuracy of the placement of a switch's beacon depends on the accuracy of the switch's internal clock and the clock's synchronization with other clocks of the network. Inaccurate placement of a beacon increases the likelihood of collisions. As discussed above, collisions can lead to missed beacons which can lead to portions or even all of a network becoming disconnected. Constructing (or reconstructing) a network can be a time and resource expensive process. As discussed above, each node must be registered and promotion procedures employed to designate switch nodes.

[0040] As said, countermeasures may be employed to reduce the likelihood of collisions and the resulting network instability, and thus to reduce the need to reconstruct a network. Small errors in beacon position can be addressed somewhat through the use of guard intervals to separate nearby beacon transmissions. The synchronization among the clocks of the network devices may be addressed somewhat through the exchange of information between devices to restore alignment.

[0041] Usage of guard intervals, however, may be not enough to keep collisions from happening. FIG. 3 illustrates

a possible placement of guard time into beacon slot **210**. As illustrated, the beacon transmissions of two switches N1 and N2 do not overlap if the transmission of a beacon by switch N1 ends at a time t_1 in the beacon slot of switch N1 before the start of a beacon transmission by switch N2 in the beacon slot of switch N2 at time t_2 . If the guard time GT is defined as the ideal gap between two consecutive beacon transmissions, the following relationship may be defined:

$$GT = t_2 - t_1 \quad (1)$$

[0042] Due to internal clock error, which may be represented as e and be expressed in parts-per-million ppm ($1 \text{ ppm} = 10^{-6}$), the time measured by a node differs from the true value of time according to:

$$t' = t(1 + e) \quad (2)$$

[0043] Thus, GT depends on the times actually measured by switches N1 and N2, so that Equation 1 can be rewritten as follows:

$$GT = t'_2 - t'_1 = t_2(1 + e_2) - t_1(1 + e_1) \quad (3)$$

[0044] If the time period T is the period of time that has to pass before the guard time GT is insufficient to prevent overlap, the following relationship may be expressed:

$$T + t_0 = t_1 = t_2 \quad (4)$$

[0045] Assuming t_0 is equal to zero, without loss of generality, the expression of Equation 3 may be rewritten as:

$$GT = t'_2 - t'_1 = t_2(1 + e_2) - t_1(1 + e_1) = T((1 + e_2) - (1 + e_1)) = T(e_2 - e_1) \quad (5)$$

[0046] By applying actual TDMA MAC protocol characteristics of an embodiment, it is possible to find T values and hence configurations where the guard time is not sufficient to protect beacon transmissions. As an example, here the PRIME MAC protocol for powerline communications is taken. PRIME uses Orthogonal Frequency-Division Multiplexing (OFDM) symbols. In PRIME version 1.4, the guard time GT is one OFDM symbol, and $e_2 - e_1$ 100 ppm, thus, from Equation 5:

$$T = GT / (e_2 - e_1) \geq 10000 \text{ OFDM symbols} \quad (6)$$

[0047] The frame length T_{frame} in PRIME can change as follows:

$$T_{frame} = T_{frame}(n) = n(276 \text{ OFDM symbols}), n = \{1, 2, 3, 4\} \quad (7)$$

[0048] Thus, T can be expressed in terms of a number of frames:

$$T = T(n) \geq (10000 \text{ symbols} / T_{frame}(n)) \approx (36/n) \text{ frames} \quad (8)$$

[0049] In the absence of reception failures, the lowest beacon transmission frequency is one beacon every super-frame (in PRIME 1.4, 32 frames). This puts an upper limit on the value of T:

$$T \leq 32 \text{ frames} \quad (9)$$

[0050] If the limit is exceeded, the guard time GT may be insufficient to prevent overlap between two interfering switches, and eventual resulting loss of synchronization. Combining Equations 8 and 9, it follows that:

$$32 \geq 36/n, \text{ that is to say } n \geq 1.125 \quad (10)$$

[0051] Thus, a guard time GT of 1 OFDM symbols is insufficient to protect against a worst case clock drift in cases of $276 * 2 = 552$ OFDM symbol frame length. In addition, because beacons may be lost due to channel errors, scenarios

employing low beacon transmission frequencies would likely face network stability issues even with the presence of guard times.

[0052] Errors in time tracking by network nodes may severely impact network performance. In an embodiment, no explicit time information is contained in beacon packets, so that nodes must rely on beacon reception times to maintain synchronization among them. In an embodiment, a protocol specification-compliant adaptive framing method is employed to maintain synchronization between nodes of a network. In an embodiment, the method is executed by nodes (e.g., switches and terminals) of the network, which may, for example, be service nodes, and does not need to be executed by the coordinator of the network. In an embodiment, each node evaluates its time tracking difference with respect to the node's parent node. In an embodiment, a node adapts its time knowledge in terms of frame duration to the frame duration of its parent node. In an embodiment, the adaptation is refreshed with every received beacon. In view of the delivery of synchronization from the coordinator to all the nodes, an embodiment facilitates automatically and gradually reducing time tracking differences between nodes, starting from the nodes directly attached to the coordinator, to the terminals farthest from the base node.

[0053] In an embodiment, the difference calculation adapts to the amount of information available. FIG. 4 is a simplified representation of an adaptive framing algorithm according to an embodiment. In FIG. 4, $f_{\Delta T}(\bullet)$ represents the adaptive framing, which provides as an output a difference estimation $S_{\Delta T}(t)$ at any time t determined based on samples collected in a time window $t-\Delta T$. As illustrated in FIG. 4, $s_0, s_{-1}, \dots, s_{-k}$ represent the collected time difference samples, from the most recent to the least recent sample, where:

[0054] t_l is the collection time of the sample and

[0055] $t_0 - t_{-k} \leq \Delta T < t_0 - t_{-k-1}$.

[0056] The amount of information corresponds to the number of samples the adaptive framing algorithm collects in the time window. For a given window length, the number of samples depends on how many beacons the node receives from its parent node in the time window. The node samples the time difference in response to reception of a beacon from the node's parent node. The number of beacons received may vary based on channel conditions (e.g., reception errors which may reduce the number of beacons received) and the network configuration (e.g., a beacon transmission frequency set lower than one beacon per frame), which may vary. Thus, the amount of samples collected may vary between a small number of samples, to a large number of samples. In an embodiment, an adaptive framing algorithm adapts to changing numbers of samples in a time window.

[0057] FIG. 5 illustrates a portion of an embodiment of a network 500 including a parent switch 502 (or coordinator) and an embodiment of a node 504 employing adaptive framing.

[0058] As illustrated, the parent switch 502 and the node 504 each include circuitry such as one or more processors P, one or more memories M, one or more discrete circuits DC (e.g., floating point circuitry, barrel shifters, etc.) and one or more finite state machines FSM, which may be used alone or in various combinations to implement the respective functions and operations of the parent switch 502 and of the node 504, such as those functions and operations discussed

herein. The parent switch 502 and the node 504 each also include their own clock 550, which is used, inter alia, to track the passage of time.

[0059] In operation, the parent switch 502 sends a beacon packet or beacon Protocol Data Unit (PDU) over a channel 506 (e.g., a wireless or wired channel, such as a power line) to the node 504. A Physical Layer (PHY) module or circuitry 508 (e.g., an interface) in the node 504 decodes the signal and extracts the beacon PDU from the signal. The physical layer circuitry 508 passes the extracted PDU to a Medium Access Control (MAC) module or circuitry 510. A PDU decoder module or circuit 512 decodes the PDU and recognizes (detects) the PDU as a beacon transmitted by the parent switch 502 of the node 504. The decoded PDU beacon is provided to a beacon receiving module or circuit BCN rx 514, which determines the reception time of the frame including the PDU beacon and provides the reception time to an adaptive framing algorithm (AFA) module or circuit 516 (as illustrated, to a sample computation module or circuit 518 of the AFA circuit 516).

[0060] As illustrated, the AFA circuit 516 comprises the sample computation circuit 518, a compensation computation module or circuit 520, and a framing tracker module or circuit 522. The sample computation circuit 518 determines a difference between a determined reception time of a frame and an expected reception time of a frame based on the determined reception time and a frame tracking signal generated by the frame tracker circuit 522. The compensation computation circuit 520 determines a frame compensation value to adjust the framing, which is provided to a framing module or circuit 524, and generates an indication that a new beacon has been received from the parent switch 502, and provides the indication that a new beacon has been received to the framing tracker circuit 522. The framing tracker circuit 522 keeps track of how many frames have been traversed, for example, based on the indication from the compensation computation circuit 520 that a new beacon has been received and a signal from the framing circuit that a new frame is being entered, and provides the information regarding how many frames have been traversed to the sample computation circuit 518 and the compensation computation circuit 520.

[0061] As mentioned above, the compensation computation circuit 520 determines a frame compensation value which is provided to a framing circuit 524 of the MAC circuit 510. The most recent frame compensation value is used by the framing circuit 524 to determine the current frame duration value of the node 504. For example, the framing circuit 524 adjusts a frame duration defined in a protocol specification based on the frame compensation value to obtain a current frame duration value of the node 504. In another embodiment, the process is iterative. For example, a previous frame duration value of the node 504 may be adjusted based on the most recent frame compensation value.

[0062] The reception time of a frame may be determined based on the reception time of the beacon and the position of the beacon within the frame (the position of the beacon within the frame may be indicated by the beacon itself). The ending time of the frame, and of frames which follow the frame before the next beacon is received from the parent switch 502, may be determined by adding the current frame duration value to the start time of the frame. This facilitates correcting the frame duration used by the node 504 to match

the frame duration used by the parent switch **502** (for example, to compensate for clock skew differences), even when a beacon is not received in every frame.

[0063] Node **504** as illustrated also comprises data processing circuitry **552**, which, in operation, may generate data for transmission on the network **500**, such as metering data or other data related to services provided by the node, or employ data received on the network **500** to control services provided by the node, such as power distribution services and related devices, etc.

[0064] The node **504** may also be a switch in the network **500**, and if so, the node **504** sends beacons to its child nodes, for example, in frames according to a frequency set by the network coordinator (see coordinator CO **102** of FIG. 1). The beacon transmission module or circuit BCN tx **526** uses frame boundaries determined based on the current frame duration value to determine the transmission time of beacons by the node **504** to its child nodes. For example, the coordinator instructs each switch (e.g., via control information included in the beacons transmitted by the coordinator and repeated by the intervening switches or via other control packets exchanged when the node is promoted to switch) when to transmit a beacon as a displacement (in OFDM symbols, time units, or whatever used metric) from a beginning of a frame in which the beacon is to be transmitted by the switch. Adjusting the frame boundaries based on the current frame duration value automatically changes the frame start time of the node **504** to match the frame start time of the parent switch **502**, which also adjusts the beacon transmission time by the node **504**. This facilitates maintaining network synchronization with all the nodes of the network **500**, as each node (e.g., node **504**) adjusts its frame boundaries to match the frame boundaries of its parent node (e.g., parent switch **502**).

[0065] While FIG. 5 illustrates various modules or circuits of the node **504** as separate components for ease of illustration, the various circuits may be combined or separated in various embodiments. For example, all or part of the functionality of the sample computation circuit **518** may be performed by the compensation computation circuit **520** in some embodiments, etc.

[0066] FIG. 6 illustrates an embodiment of a method or subroutine **600** of adaptive framing, which may be employed, for example, by the nodes of FIG. 1 (e.g., switches **104** and terminals **106**), or by the node **504** of FIG. 5. For convenience, the method **600** of FIG. 6 will be described with reference to the network **500** of FIG. 5.

[0067] The method **600** starts at **602**. The method **600** may start, for example, as soon as node **504** is registered with the network **500** (e.g., the node **504** is associated with the parent switch **502**, and the node **504** is set up to receive and process beacons).

[0068] The method **600** proceeds from **602** to **604**. At **604** through **608**, the node **504** initializes the method **600**. At **604**, the node **504** determines whether a first beacon is received in a frame. For example, in a connection between the node **504** and its parent switch **502**, while time goes by with multiple frames, only some of the frames may include a beacon from the parent switch **502**. When it is determined at **604** that a first beacon has been received in a frame (e.g., a beacon has been detected in a frame), the method **600** proceeds from **604** to **606**. When it is not determined that a

first beacon has been received in a frame, the method **600** returns to **604** to determine whether a first beacon is received in the next frame.

[0069] At **606**, a variable tracking a number of elapsed frames, $\#_elapsed_frames$, is initialized by the node **504**. The variable $\#_elapsed_frames$ may be, for example, initialized to -1 . The method **600** proceeds from **606** to **608**. At **608**, the node **504** initializes a compensation value, $comp$, which may be used to adjust the current frame duration employed by the node **504**. The compensation value $comp$, may be, for example, initialized to zero. The method proceeds from **608** to **610**.

[0070] At **610**, the node **504** determines whether a beacon is received in a frame, and thus whether to collect a sample for use in determining a clock compensation value. When it is determined at **610** that a beacon is received in a frame, the method **600** proceeds from **610** to **612**. When it is not determined at **610** that a beacon is received in a frame, the method **600** returns to **610** to see if the next frame includes a beacon.

[0071] At **612**, the node **504** determines the real (measured) start time SoF_{real} of the frame in which the beacon is received. The real start time SoF_{real} of the frame may, for example, be determined based on the following equation:

$$SoF_{real} = bcn_rx_time - td_bcn_pos, \quad (11)$$

where bcn_rx_time is the time when the beacon is received and td_bcn_pos is the time interval between the start of the frame and the position of the beacon in the frame. The position of the beacon in the frame (expressed in OFDM symbols, time units, or whatever used metric) is included in the beacon. The method **600** proceeds from **612** to **614**.

[0072] At **614**, the node **504** determines a reference or theoretical start time SoF_{theo} of the frame in which the beacon is received, assuming no clock skew. The reference or theoretical start time SoF_{theo} of the frame may, for example, be determined based on the following equation:

$$SoF_{theo} = SoF_{real}^{(-1)} + T_{frame} \cdot \#_elapsed_frames, \quad (12)$$

where $SoF_{real}^{(-1)}$ is the real start time of the previous frame in which a beacon was received, T_{frame} is the length of a frame as defined in the communication protocol, and $\#_elapsed_frames$ is a number of frames that have elapsed since the previous frame in which a beacon was received. FIG. 7, discussed in more detail below, illustrates an example embodiment of a method of determining the number of elapsed frames. The method **600** proceeds from **614** to **616**.

[0073] At **616**, the node **504** determines a sample compensation value associated with the received beacon $comp_{sample}$ (a beacon compensation value). The beacon compensation value associated with the received beacon $comp_{sample}$, may be determined, for example, based on the following equation:

$$comp_{sample} = (SoF_{real} - SoF_{theo}) / (\#_elapsed_frames) \quad (13)$$

[0074] The method **600** proceeds from **616** to **618**. At **618**, the node **504** determines a compensation filter parameter α , which may be a function of the number of elapsed frames $\#_elapsed_frames$. Table 1 illustrates example values of the compensation filter parameter for the number of frames. Other functional relationships between the compensation filter parameter α and the $\#_elapsed_frames$ may be employed.

TABLE 1

Example Compensation Filter Parameter Values	
#_elapsed_frames	α
1	$1/8$
2	$1/4$
$3 \leq \#_elapsed_frames \leq 8$	$1/2$
$\#_elapsed_frames \geq 9$	1

[0075] The method 600 proceeds from 618 to 620. At 620, the node 504 determines a frame compensation value comp, which may be applied to a frame length defined in a protocol specification to obtain a current frame duration value of the node 504. The frame compensation value comp may be determined, for example, according to:

$$\text{comp} = (1 - \alpha) \cdot \text{comp} + \alpha \cdot \text{comp}_{\text{sample}} \quad (14)$$

[0076] In other embodiments, other filtering mechanisms may be employed, which may require other or different parameters from α above.

[0077] The method 600 proceeds from 620 to 622. At 622, the node 504 determines a current frame duration value to be employed by the node 504 based on a frame length defined in the protocol specification and the frame compensation value comp. The method proceeds from 622 to 624.

[0078] At 624, the node 504 determines whether it is finished performing adaptive framing. When it is determined at 624 that adaptive framing is finished, the method proceeds from 624 to 626 where the method stops. When it is not determined at 624 that adaptive framing is finished, the method proceeds from 624 to 610 to wait for the next received beacon.

[0079] Embodiments of the method 600 may include acts not shown in FIG. 6, may omit acts shown in FIG. 6, and may perform acts shown in FIG. 6 in various orders. For example, an embodiment of a method of determining a number of elapsed frames since the last beacon was received, such as the embodiment illustrated in FIG. 7, may be incorporated into the method 600 in an embodiment.

[0080] FIG. 7 illustrates an embodiment of a method or subroutine 700 of determining the number of elapsed frames #_elapsed_frames, since the last beacon sample was received (e.g., since the last beacon was successfully received from the parent switch 502), which may be employed, for example, by the nodes of FIG. 1 (e.g., switches 104 and terminals 106), or by the node 504 of FIG. 5. An embodiment of the method of tracking the number of elapsed frames 700 may be employed, for example, by the method 600 of adaptive framing of FIG. 6. For convenience, the method 700 of FIG. 7 will be described with reference to the network 500 of FIG. 5.

[0081] The method 700 starts at 702 and proceeds to 704. At 704, the node 504 determines whether a beacon is received in a current frame. This may be done, for example, by the framing tracker circuit 522 based on a signal generated by the compensation computation circuit to indicate a new beacon has been received from the parent switch 502. When it is determined at 704 that a beacon has been received in the current frame, the method 700 proceeds from 704 to 706. When it is not determined that a beacon has been received in the current frame, the method 700 proceeds to 708.

[0082] At 706, a variable tracking a number of elapsed frames, #_elapsed_frames, is initialized by the node 504.

The variable #_elapsed_frames may be, for example, initialized to -1. The method 700 proceeds from 706 to 704.

[0083] At 708, the node 504 determines whether a new frame is starting. This may be done, for example, based on a signal generated by the framing circuit 524 to indicate a new frame is being entered, for example, based on a signal from the clock 550 and the current frame duration value employed by the node 504. When it is determined at 708 that a new frame is starting, the method proceeds from 708 to 710, where the node 504 increments the number of elapsed frames #_elapsed_frames. The method 700 proceeds from 710 to 704.

[0084] Embodiments of the method 700 may include acts not shown in FIG. 7, may omit acts shown in FIG. 7, and may perform acts shown in FIG. 7 in various orders. For example, an embodiment may include acts to determine whether method 700 should stop tracking the number of elapsed frames.

[0085] Some examples, with reference to FIG. 5 for convenience, illustrate how the compensation employed by an embodiment of the method 600 of FIG. 6 facilitate accounting for clock skews of a node (e.g., node 504) and the node's parent switch (e.g., parent switch 502) to synchronize the node with the parent switch. The clock skew of the parent switch 502 affects the beacon transmission time and when the beacon itself is received (e.g., bcn_rx_time), and hence the start of the frame measured by the node. The clock skew of the node 504 affects the theoretical frame length (e.g., T_{frame}), as well as the measurement of bcn_rx_time.

[0086] Equation 13 may be rewritten as follows by substituting from Equation 12:

$$\text{comp}_{\text{sample}} = ((\text{SoF}_{\text{real}} - \text{SoF}_{\text{real}}^{(-)}) / (\#_elapsed_frames)) - T_{\text{frame}} \quad (15)$$

[0087] In a first scenario, both the parent switch's 502 and the node's 504 clocks are accurate. In this case, $\text{SoF}_{\text{real}} - \text{SoF}_{\text{real}}^{(-)}$ is equal to $\#_elapsed_frames \cdot T_{\text{frame}}$ and $\text{comp}_{\text{sample}}$ is zero, and (correctly) no compensation is applied.

[0088] In a second scenario, the parent switch's 502 clock is accurate, and the node's 504 clock is fast. In this case, $\text{SoF}_{\text{real}} - \text{SoF}_{\text{real}}^{(-)}$ is accurate on an absolute time scale, but it is measured longer than $\#_elapsed_frames \cdot T_{\text{frame}}$ by the node 504. The compensation sample $\text{comp}_{\text{sample}}$ is non-zero (positive), and the compensation causes the node 504 to enlarge its time frame (e.g., to increase the current frame duration value). This is correct because the node's 504 clock skew is causing the node 504 to use shorter frame durations than the parent switch 502.

[0089] In a third scenario, the parent switch's 502 clock is fast, and the node's 504 clock is accurate. In this case, $\text{SoF}_{\text{real}} - \text{SoF}_{\text{real}}^{(-)}$ is accurate for purposes of the parent switch 502, but it is shorter than $\#_elapsed_frames \cdot T_{\text{frame}}$ on an absolute time scale, and it is measured as shorter than $\#_elapsed_frames \cdot T_{\text{frame}}$ by the node 504. T_{frame} is accurate for the node 504 and on the absolute time scale. The compensation sample $\text{comp}_{\text{sample}}$ is non-zero (negative), and the compensation causes the node 504 to shrink its time frame (e.g., to decrease the current frame duration value) to synchronize with the frame duration of the parent switch. This is correct because the node 504 tunes its behavior to that of the parent switch 502.

[0090] In a fourth scenario, the parent switch's 502 clock and the node's 504 clocks are fast with the same skew. In this case, $\text{SoF}_{\text{real}} - \text{SoF}_{\text{real}}^{(-)}$ is accurate for purposes of the

parent switch **502**, but it is shorter than $\#_elapsed_frames \cdot T_{frame}$ on an absolute time scale and it is accurate for purposes of the node **504**. T_{frame} is accurate for purposes of the node **504** and is shorter than the theoretical frame time on the absolute time scale. The compensation sample $comp_{sample}$ is zero, and no compensation is applied by the node. This is correct because the node **504** and the parent switch **502** are using the same time knowledge.

[0091] In a fifth scenario, the parent switch's **502** clock is fast, and the node's **504** clock is slow. In this case, $SoF_{real} - SoF_{real}^{(-)}$ is accurate for purposes of the parent switch **502** and it is shorter than $\#_elapsed_frames \cdot T_{frame}$ on an absolute time scale and it is even shorter for the node **504**. T_{frame} is accurate for the node **504** and is longer than the theoretical frame time on the absolute time scale. The compensation sample $comp_{sample}$ is non-zero (negative), and the node correctly shrinks its frame duration.

[0092] In an embodiment of a method of adaptive framing, an exponential moving average has been chosen to update the compensation. This may facilitate: reducing computational time (the operations are not complex); taking the sample history into account without buffering the samples; adjusting the amount of compensation based on the amount of available information; and selecting filtering parameter(s) (e.g., compensation filter parameter α) based on the impact of the computations on the processing speed. A number of factors may be considered when defining the compensation filter parameter(s).

[0093] For example, a relatively high number of received beacons indicates there are more samples per unit of time. This may indicate the average as having a high level of confidence. The average may also filter away oscillations which may be more likely when the sampling frequency is higher. Thus, more samples may be required to significantly change the compensation value $comp$. In this case, lower values may be assigned to the compensation filter parameter α .

[0094] In another example, a relatively low number of received beacons indicates there are fewer samples per unit of time. This may indicate the impact of the average should be reduced to facilitate a faster response to changing clock skews. Also, the impact of oscillations may be attenuated when there is more time between samples. In this case, higher values may be assigned to the compensation filter parameter α . Simulations have indicated the values in Table 1, above, work well in an embodiment, and work well with, and without, the use of floating point units, which facilitates the use of adaptive framing in simpler hardware configurations. It is noted that for a compensation filter parameter of $\frac{1}{2}$ (and powers thereof) in an embodiment, the compensation can be implemented by shifting bits. The simulations also show significant improvement in maintaining synchronization in scenarios presenting significant clock skew differences and lost beacons.

[0095] Embodiments may be implemented, for example, in TDMA MAC protocols, in multi-hop and single-hop networks, in wired and wireless networks, and facilitate nodes maintaining synchronization without explicit exchanges of temporal information to compensate for clock skew. Embodiments may be implemented just at the reception side, and facilitate a node adjusting its frame length to match the frame length of its parent switch, without the use of special packets containing temporal control information.

[0096] Some embodiments may take the form of or include computer program products. For example, according to one embodiment there is provided a computer readable medium including a computer program adapted to perform one or more of the methods or functions described above. The medium may be a physical storage medium such as for example a Read Only Memory (ROM) chip, or a disk such as a Digital Versatile Disk (DVD-ROM), Compact Disk (CD-ROM), a hard disk, a memory, a network, or a portable media article to be read by an appropriate drive or via an appropriate connection, including as encoded in one or more barcodes or other related codes stored on one or more such computer-readable mediums and being readable by an appropriate reader device.

[0097] Furthermore, in some embodiments, some of the systems and/or modules and/or circuits and/or blocks may be implemented or provided in other manners, such as at least partially in firmware and/or hardware, including, but not limited to, one or more application-specific integrated circuits (ASICs), digital signal processors, discrete circuitry, logic gates, standard integrated circuits, state machines, look-up tables, controllers (e.g., by executing appropriate instructions, and including microcontrollers and/or embedded controllers), field-programmable gate arrays (FPGAs), complex programmable logic devices (CPLDs), etc., as well as devices that employ RFID technology, and various combinations thereof.

[0098] Some embodiments may combine illustrated blocks, circuits or methods, omit illustrated blocks, circuits or methods, include additional blocks, circuits or methods and various combinations thereof. The various embodiments described above can be combined to provide further embodiments. Aspects of the embodiments can be modified, if necessary to employ concepts of the various patents, applications and publications to provide yet further embodiments.

[0099] These and other changes can be made to the embodiments in light of the above-detailed description. In general, in the following claims, the terms used should not be construed to limit the claims to the specific embodiments disclosed in the specification and the claims, but should be construed to include all possible embodiments along with the full scope of equivalents to which such claims are entitled. Accordingly, the claims are not limited by the disclosure.

1. A device, comprising:

means for receiving a data stream of a network;

means for detecting a beacon packet in a frame of the data stream, wherein a frame is a period of time having a defined frame duration;

means for determining a frame compensation value based on a start time of the frame, a reference start time of the frame, and a number of elapsed frames; and

means for determining a current frame duration value based on the determined frame compensation value and the defined frame duration.

2. The device of claim 1 wherein the frame compensation value is determined by applying a filter based on the number of elapsed frames.

3. The device of claim 2 wherein a filter parameter is selected based on the number of elapsed frames.

4. The device of claim 3, comprising means for determining a sample compensation value based on the start time of the frame, the reference start time and the number of

elapsed frames, wherein the frame compensation value is determined by applying the filter to the sample compensation value.

5. The device of claim 1, comprising:
means for determining the reference start time of the frame based on a start time of a previous frame in which a beacon was detected, the defined frame duration and the number of elapsed frames.

6. The device of claim 1, comprising:
means for detecting the number of elapsed frames.

7. The device of claim 6 wherein the number of elapsed frames is a number of frames elapsed since a frame in which a previous beacon was detected, and the means for determining the number of elapsed frames initializes the number of elapsed frames when a beacon is detected and increments the number of elapsed frames when a new frame is started.

8. The device of claim 1, comprising
means for controlling transmission of a beacon at a transmission time based on the current frame duration value.

9. The device of claim 1 wherein the network is a powerline network and the data stream travels on cables used to transport electricity.

10. The device of claim 1 wherein,
the start time of the frame SoF_{real} is determined according to:

$$SoF_{real} = bcn_rx_time - td_bcn_pos,$$

where bcn_rx_time is a time when the beacon is received and td_bcn_pos is a time interval between the start of the frame and the position of the beacon in the frame;

the reference start time SoF_{theo} is determined according to:

$$SoF_{theo} = SoF_{real}^{(-)} + T_{frame} \cdot \#_elapsed_frames,$$

where $SoF_{real}^{(-)}$ is a start time of a previous frame in which a beacon was received, T_{frame} is a length of a frame, and $\#_elapsed_frames$ is a number of frames that have elapsed since the previous frame in which a beacon was received; and

the frame compensation value $comp_{sample}$ is determined according to:

$$comp_{sample} = (SoF_{real} - SoF_{theo}) / (\#_elapsed_frames).$$

11. An integrated circuit having circuitry, which, in operation, manages a Time Division Multiple Access (TDMA) Medium Access Control (MAC) process, the process comprising:

detecting a beacon packet in a frame of a network data stream, wherein a frame is a period of time having a defined frame duration;

determining a frame compensation value based on a start time of the frame, a reference start time of the frame, and a number of elapsed frames; and

determining a current frame duration value based on the determined frame compensation value and the defined frame duration.

12. The integrated circuit of claim 11 wherein the frame compensation value is determined by applying a filter based on the number of elapsed frames.

13. The integrated circuit of claim 11 wherein the circuitry includes an interface, which, in operation, receives the network data stream.

14. A device, comprising:

a physical layer circuit, which, in operation, receives a data stream of a network and extracts a beacon protocol data unit (PDU) from a frame in the data stream, wherein a frame is a period of time having a defined duration; and

Time Division Multiple Access (TDMA) Medium Access Control (MAC) circuitry, coupled to the physical layer circuit, wherein the TDMA MAC circuitry includes:

a PDU decoder, which, in operation, decodes the beacon PDU extracted by the physical layer circuit;

a beacon receiving circuit, coupled to the PDU decoder, and which, in operation, determines a reception time of the frame including the beacon PDU;

an adaptive framing circuit, coupled to the beacon receiving circuit, and which, in operation, determines a frame compensation value based on the reception time of the frame, a reference reception time of the frame, and a number of elapsed frames; and

a framing circuit, coupled to the adaptive framing circuit, and which, in operation, determines a current frame duration value based on the determined frame compensation value and the defined frame duration.

15. The device of claim 14 wherein the adaptive framing circuit, in operation, determines the frame compensation value by applying a filter based on the number of elapsed frames.

16. The device of claim 15 wherein the adaptive framing circuit, in operation, selects a filter parameter based on the number of elapsed frames.

17. The device of claim 14, wherein the adaptive framing circuit comprises:

a sample computation circuit;

a compensation computation circuit; and

a framing tracker circuit, wherein,

the sample computation circuit, in operation, determines a difference between a determined reception time of a frame and an expected reception time of a frame based on the determined reception time and a frame tracking signal generated by the frame tracker circuit, and the compensation computation circuit, in operation, determines the frame compensation value.

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