

Ad-Hoc Association of Pre-determined ZigBee Devices

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Abstract—In pervasive sensor networks with high densities, similar networks might overlap, resulting in different coordinators for end devices to associate with. This can result in several problems, especially for home monitoring and hospital scenarios, where easy, fast, and accurate association of pre-determined devices is needed. Due to the rapidly changing environments in these scenarios, however, association schemes are required that allow ad-hoc associations of pre-determined devices in this context.

In this paper, we describe the problems for this particular scenario with respect to the current standard methods of association and present multiple solutions to alleviate the problems encountered. We additionally present a generalized process flow for combining the different solutions into a single solution that can be implemented for future sensing and coordinating nodes.

Index Terms—ZigBee, IEEE802.15.4, home monitoring, sensor networks

I. INTRODUCTION

Wireless Sensor Networks (WSNs) have attracted a great body of research in the past. More recently, practical applications have emerged that are widely based on the ZigBee/IEEE802.15.4 standard, see [1], [2] for the current revisions. WSNs can be used in very different application scenarios covering home automation, health care, and military applications, to name a few.

Health care applications have in particular attracted recent research, see, e.g., [3]–[12]. In typical health care application scenarios, the sensor nodes (or end devices) collect information from one or more sensors attached to them, e.g., blood pressure, and send this information to a data gathering and analyzing node, which typically employs the ZigBee coordinator function as well. The coordinator forms the ZigBee network with a specific network ID (PANID) and extended network ID (EPID) on one of multiple logical channels. In addition, the data coordinator is typically connected through other networks to allow for data forwarding and other network-based functionalities. Additional tiers may be present to filter and process data, such as those presented in [13]. In [6], the authors present a general case for (mobile) health care applications based on sensors and provide an extensive list of sensors and their applications in pervasive health care.

Some examples of health care scenarios are:

- Hospitals where multiple beds are in close proximity,

- Rehabilitation centers with multiple patients being monitored, or
- Monitoring of patients in their private home.

For typical health care scenarios, it can very well be assumed that end devices are in the range of multiple similar networks with similar network/device descriptors. In turn, end devices have to decide which network on what logical channel to join. By default, the ZigBee standard defines the manner in which these end devices connect to existing networks. There are, however, no specific measures in the standard that determine for a desired pre-determined association which network an end device will join if multiple networks with the same underlying characteristics exist and no additional information is available.

The authors of [9] present a patient centered system for patient health and environment monitoring and propose a health care profile and cluster functions for use within the ZigBee standard framework. They do not provide any ad-hoc network device association, but employ a middleware solution. In [10], the authors propose a system with reliable transmissions where users enter the end device information into an external device. Entering the detailed information, however, is not always desired or feasible under operating conditions. Other approaches use pre-determined channels and network IDs to make sure end devices join the pre-specified networks.

Overall, current solutions do not allow for easy ad-hoc configuration of a network that is only comprised of pre-determined nodes. The ZigBee standard does not provide means for this type of association, but relies on predetermined configuration parameters or fully automatic network configuration. Both approaches are not suitable for easy device exchange or network re-configuration if only a specific set of devices should join a network.

The remainder of this paper is outlined as follows. In Section II, we discuss current mechanisms outlined in the ZigBee standard that address device association in-band, i.e., within the provided wireless communications system, and outline enhancements to the current mechanisms before we discuss out-of-band solutions, i.e., through external communications means, to solve the problem of device associations. In Section III, we describe a generalized scheme before we conclude in Section IV.

II. SOLUTIONS FOR INITIAL DEVICE ASSOCIATION

Solutions exist for forbidding nodes to join a network through configuration parameters within the ZigBee stack. This can be realized, e.g., through a switch or button on the coordinator. Alternatively, if the network uses a trust center, the communication can be encrypted using previously shared keys. If a ZigBee end device becomes active, it will try to join the most favorable network that allows joining. The standard specifies that these new nodes should select the network to join by actively scanning for networks first. The default method of association for joining a network is illustrated in Figure 1. Note that there were no significant changes from the previous ZigBee 2006 standard for the joining methodology. As observed in Figure 1, the joining is based on an active scan (or alternatively a passive scan in the ZigBee 2006 standard) of the logical channels that were previously configured. The result of an active/passive scan is a list of suitable networks, their respective logical channels, and additional ZigBee descriptors further describing the individual networks. As stated in the ZigBee standard, the joining should take place to the coordinator or router with the minimum network depth or amongst a group of devices that fulfill this requirement. This approach, however, does not necessarily result in joining the desired network.

In an area densely populated with coordinators and end devices, the new node might select the wrong channel/network combination to join, as descriptors used in these networks will be identical, e.g., multiple patients in the same area in a hospital. Additionally, multiple coordinators might be simultaneously configured to allow network joining. It is hence a necessity to allow for easy ad-hoc association of pre-determined new nodes with specific coordinators. One method to do this is to pre-determine the information required and enter it into the sensing nodes and/or coordinators. Entering information by hand, e.g., using a PDA or tablet PC, before is-

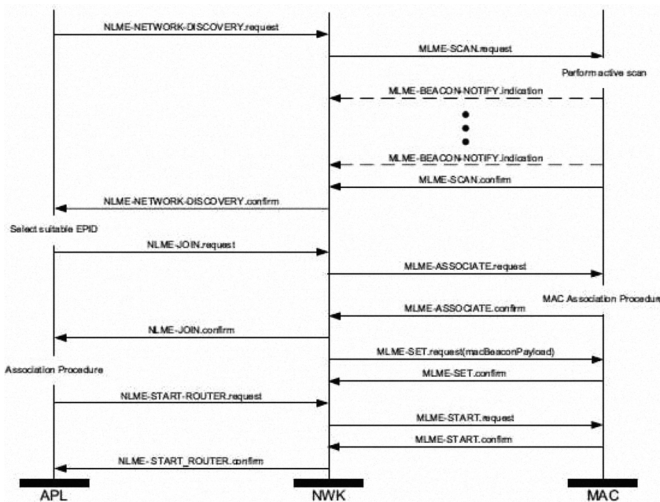


Fig. 1. Association procedure for network joins of end devices according to the ZigBee 2007 standard [1].

using the nodes adds time and the element of data entry errors and is therefore not desirable. Also, coordinators may re-select a different channel and/or network ID over time, which will add significantly to the required interaction and management. In the following, we outline two different solutions to the end device association problem.

A. Ad-Hoc Association Based on ZigBee/802.15.4

In this section, we discuss possibilities for the ad-hoc association of pre-determined end devices according to the ZigBee 2007 [1] and underlying IEEE802.15.4 [2] specifications. The IEEE802.15.4 Medium Access Layer (MAC), which is part of the ZigBee standard, provides additional scanning methods. The results of an active scan directly performed by the MAC layer include link quality descriptors for each of the different networks found. The IEEE802.15.4 standard explicitly leaves their usage up to the network and application layers [2]. As the ZigBee standard uses the network depth as final joining indicator, this is the area of improvements to implement the ad-hoc association of predetermined ZigBee devices.

Note that access to the MAC layer functions is implementation-specific and might require actions before the actual ZigBee stack is initialized. If an active scan is initiated prior ZigBee initialization, the results of the scan need to be stored in memory for application retrieval while setting the initial ZigBee configuration parameters. Note that the end device needs to determine the extended PANID (EPID) of the network to join. This allows the end device to successfully set the configuration parameters of the ZigBee stack to allow association only with the identified coordinator (PAC or GAC). A typical approach to set the EPID is to use the IEEE MAC address of the coordinator, which is a unique identifier of the coordinator. The individual steps for the network coordinator are:

- 1) Initiate ZigBee stack.
- 2) Set ZigBee configuration parameters according to stored (default) values.
- 3) Start ZigBee (network formation).
- 4) Set runtime parameters, e.g., disallow joining of new nodes to network.
- 5) If 'Allow Join' initiated through external signal, e.g., through external button:
 - a) Receive ZigBee join request.
 - b) Check if device descriptor matches allowable descriptors.
 - c) Join device.
 - d) Query device for IEEE MAC address.
 - e) Store IEEE MAC address (and other descriptors) in memory (non-volatile).

The individual steps for an end device after an external signal for initial association (network joining) is received are as follows:

- 1) Initiate MAC-level active scan over all (configured) logical channels and receive network descriptors in turn.

- 2) From the list of networks found, select the one with the highest link level quality above a certain threshold, e.g., 98.5% (returned value / 255).
- 3) Store the channel, PANID, and extended PANID (IEEE MAC address of the coordinator) in memory (non-volatile or volatile).
- 4) Initiate ZigBee stack.
- 5) Set ZigBee configuration parameters according to stored values.
- 6) Start ZigBee and join the determined PAN.

To determine which network to join in the scheme outline above, the association process should be cancelled and repeated after a random amount of time, if multiple suitable networks were found. This should allow other simultaneously ongoing association procedures in the vicinity of the node under consideration to complete their association process or time out as well. The node needs to have some means of alerting the user of this state, e.g., through an LED, so that the user can repeat the association procedure.

This approach, however might still yield false associations if we consider different ZigBee implementations using radio modules with different transmissions power, e.g., 1mW or 10mW, which requires further investigations. Once this initial association is complete, downtimes of the coordinator no longer affect the re-creation of the network and re-association of devices, as the IEEE MAC address is a unique device identifier. We additionally note that device removal from the network can be handled in a similar manner.

1) Implementation Example: We implemented the link quality based ad-hoc association scheme using Integration's IA OEM-DAUB1 2400 USB dongle, which implements the IEEE 802.15.4 standard in hardware and the ZigBee 2006 standard in software drivers. (Note that at the time of writing, Integration was acquired by Silicon Labs.)

In our prototypical implementation, the coordinator is implemented as Windows or Linux application. The coordinator selects a logical channel from a range of channels to use and uses its IEEE MAC address as extended PAN ID. The end device is implemented in Java and C, utilizing the provided Integration ZigBee stack for Linux. The end device performs an initial active scan using IEEE 802.15.4 MAC layer primitives over the same range of logical channels the coordinator can utilize for the network formation. From the list of networks found, the end device selects the first network with the highest link quality to join. After the MAC-level scan is completed, the ZigBee stack is started and the results from the MAC-level scan are used to set the ZigBee initialization parameters.

B. Device Association Based on External Solutions

In the following, we describe two external solutions to the end device association problem, namely one that is based on external reading devices that are connected to the coordinator and one that is based on using the network connectivity of the coordinator, e.g., through dial-in or dial-up connections over phone lines utilizing a modem.

In ZigBee networks, the only fixed unique identifier is the IEEE MAC address of the nodes comprising the network. Network channels used, PANIDs (network identifiers), extended PANIDs (extended network identifiers), and network addresses are assigned ad-hoc through the coordinator forming the network. The ZigBee standard provides means for the direct joining of nodes. In such scenario, the coordinator has knowledge of the IEEE MAC address of the node or end device to add to the network. The coordinator performs a direct join through the ZigBee NLME-DIRECT-JOIN.request primitive using the IEEE MAC address of the node to join. As the ZigBee standard describes, this makes the new end device directly a member of the network. The directly joined node in turn has to start the orphaning procedure before trying to actively join any network. This procedure uses the network rejoining methods provided through the standard.

Different methods to enter the end device's information (IEEE MAC address) can be used, e.g., a local web server running on the coordinator or using other external devices through which the information is entered into the coordinator. Without loss of generalization, entering device information by hand is prone to data entry errors, and hence not desirable. Alternative means should be provided to make an end device's IEEE MAC address available to the coordinator for the direct join procedure.

1) Readers and Tags: In the following, we assume that the ZigBee coordinator in the network has an additional reading device through which information from *tags* can be obtained. We note that we use the term *tag* synonymously for different technological solutions, e.g., RFID tags or smart cards. The tag reader attached to the coordinator will read the IEEE MAC address directly from the individual tags, which are distributed collectively with the end devices, e.g., as an RFID tag (e.g., a label) attached to the end device. The tags in turn need to be programmable and hold at least 64bit of information. Most newer RFID tags have a more than sufficient capacity to store this amount of information. Similarly, smart cards have enough capacity to store the required information. The maximum reading distance for the coordinator's tag reader should be as short as possible to prevent interference from other tags that may be present. An example scenario for external readers and tags to solve the association problem of end devices is as follows:

- 1) Customer receives coordinator and end devices
- 2) Customer plugs in coordinator, the coordinator starts network
- 3) Customer scans (additional) end device at the coordinator's reader, e.g., by pushing an external button
 - a) Coordinator adds end device to network through direct join
- 4) Customer powers on end device(s)
 - a) End device uses orphan procedure to determine it is member of coordinator's network
 - b) End device joins network

As illustrated by the example above, the requirements for the customer or user of the overall system are fairly minimal. We additionally note that removing devices from the network can be handled in a similar manner, e.g., through another external button on the coordinator.

2) *Dial-In or Dial-Out*: For this example, we assume that the coordinator has network connectivity, e.g., through the telephone system using a conventional modem. In this configuration, an external entity or service provider is responsible for the device management. The external entity could be a home health care agency. The coordinator can employ a dial-in approach, e.g., after an external button is pushed, the coordinator's modem dials into a central server and obtains information about the devices issued to the customer or user of the system. After the coordinator retrieves the information, it is used to directly join the end devices to the network. As centralized management is required in this scenario, all devices issued to the customer or user of the system need to be registered with the external service provider. In this scenario, a customer would perform the following steps:

- 1) Customer receives coordinator and end devices
 - a) Item was previously entered into the external service provider's database
- 2) Customer connects coordinator (including gateway functions) to telephone network, powers on, and pushes external synchronization button.
- 3) Coordinator dials into service provider and
 - a) If first network initialization, forms new network
 - b) Retrieves information about all devices
 - c) Uses direct join procedure for all new devices
- 4) Customer powers on end device(s)
 - a) End device uses orphan procedure to determine it is member of coordinator's network
 - b) End device joins network

As outlined in the envisioned process of setting up the network, here the association between coordinator and end devices takes place at an external service provider. The coordinator synchronizes with the external provider to obtain information about all end devices that should be members of its network. In a manner similar to the one outlined above, the service provider could use a dial-in approach to update the coordinator's list of network members in case of exchanges or removals.

III. GENERAL DEVICE ASSOCIATION SOLUTION

In this section, we provide a generalized scheme that takes the different approaches to solve the device association into account.

In general, the coordinator should load the information for all nodes that were joined in the last network configuration from persistent memory. Afterwards, the coordinator should perform direct join procedures for each node in the previous network. It is important that for (re-)creation of a network, the coordinator uses the same extended PAN ID (EPID) that

was used before. This allows each end device to re-establish contact with the correct coordinator.

An end device or node shall first check if an external signal for usage of the link quality association scheme is present. In that case, the node shall attempt to use the association scheme outlined in Section II-A. If no external signal is present, the node should perform the orphan join procedure. If not successfully (re-)joined to a network through the orphan procedure, the node should load the last configuration for the coordinator (or any other parent, i.e., a router) from persistent memory and use the normal join method to join a network with the last network information. Only if the different approaches to join a network fail should the node give up and indicate an error to the user.

In the following, we discuss the coordinator and end device processes in greater detail.

A. Coordinator

We illustrate the process for the initial start of the coordinator process in Figure 2. As illustrated, the coordinator starts with the configuration of the ZigBee parameters and starts the network. The most important parameter to be considered in the schemes presented in Section II is the extended PAN ID (EPID). After the network has been formed by the coordinator, the network should be configured to generally disallow joins. This will allow the user through interaction with the coordinator device, e.g., through an external button, to allow joins to the network later and keep unwanted nodes off the network. After the network is formed, the coordinator should add any previously configured nodes into the network using the direct join procedures.

If a new end device should be added according to the

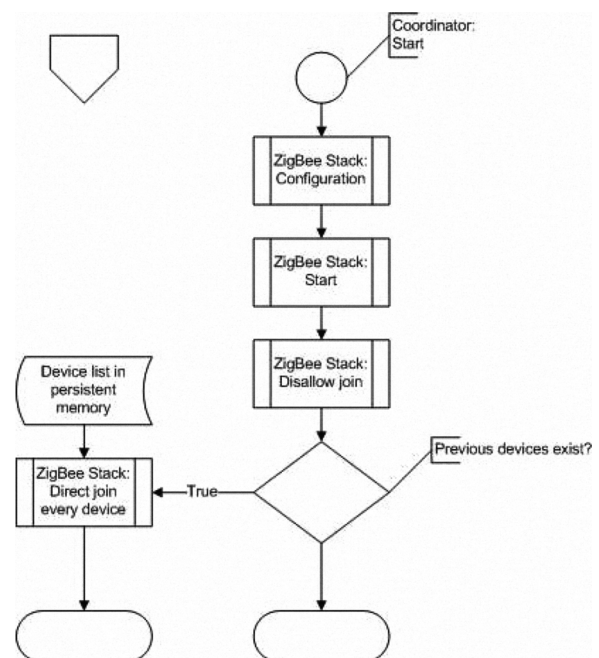


Fig. 2. Coordinator start procedure.

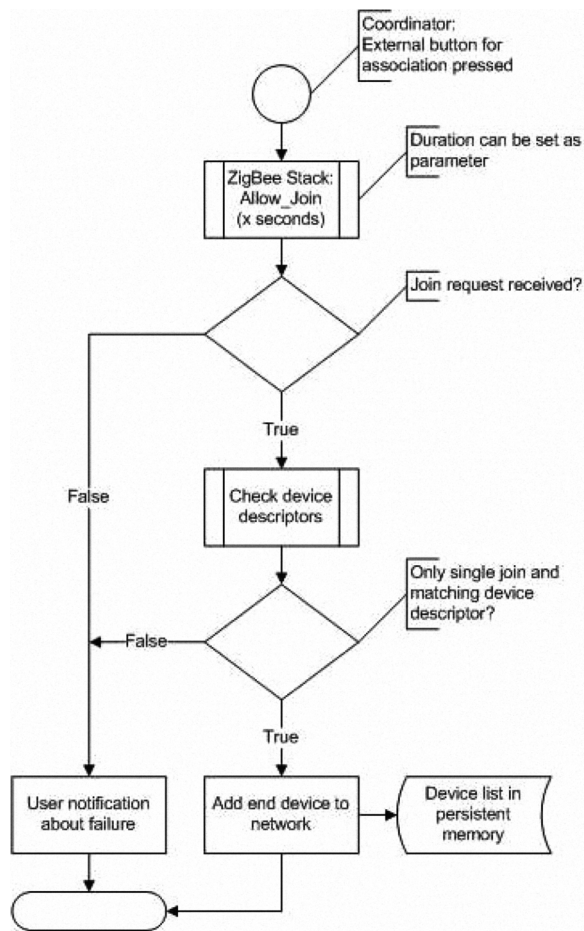


Fig. 3. Coordinator enable join procedure.

scheme outlined in Section II-A, the coordinator will allow temporarily new devices to join the network, as illustrated in Figure 3. The ZigBee standard provisions a parameter through which the time to join can be set. Generally, it might be advisable to only allow joining of new devices for a short period of time, e.g., less than a minute, to minimize interference of join procedures of adjacent or overlapping networks. If multiple join requests are received during the allowable join duration, then multiple network joins are performed in the vicinity and the user should be informed, e.g., through an LED, that the association did not complete. Only if a single join is received during the period of allowable joins should new devices be associated with the coordinator to remove ambiguities.

The coordinator should additionally have some means of removing all previously associated end devices from its memory, which is illustrated in Figure 4. If joining operations failed or to re-issue the coordinator, all previously joined end devices should be removed from the coordinator. We note that a process similar to the initial association might be used to remove nodes selectively from the network.

B. End Device

We illustrate the general process for end devices using a generalized approach in Figure 5. After initial start of the end

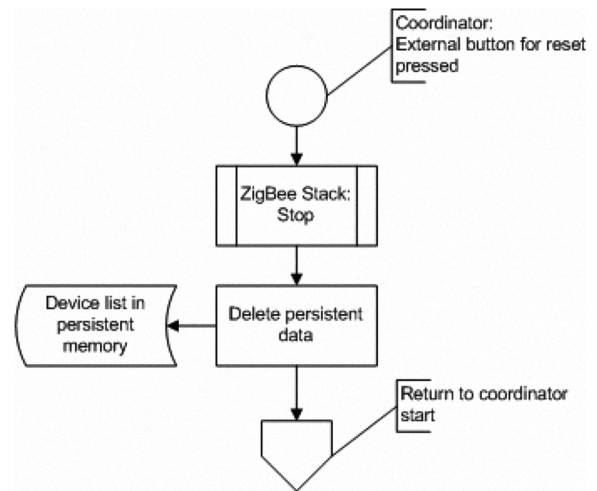


Fig. 4. Coordinator reset procedure.

device (or at any other point in time), if an external signal is received, e.g., through an external button, the end device performs the association procedures based on the link quality outlined in Section II-A. If no single network fulfilling the preset requirements is found, the process should end with a notification that the attempt should be retried, e.g., through an external device LED. If no external button was pressed or if another association scheme is used, such as the ones outlined in Section II-B, the end device should perform an initial orphan scan to determine if it should re-join any existing network. If no previous network associations exist, the device is not a member of any networks nearby and should indicate an error to the user.

IV. CONCLUSION

In this paper, we outlined challenges for the correct association of devices within a wireless sensor system based on the IEEE802.15.4 or ZigBee standards. Off-the shelf sensor nodes may not associate to the desired coordinators in an area that is densely populated with those. To remedy this problem, we introduce a link-quality based scheme and two schemes that use external information to allow the correct association of end devices and coordinators with minimal or simplistic user interference. We finally provide a synthesis of the different possibilities in a generalized process description.

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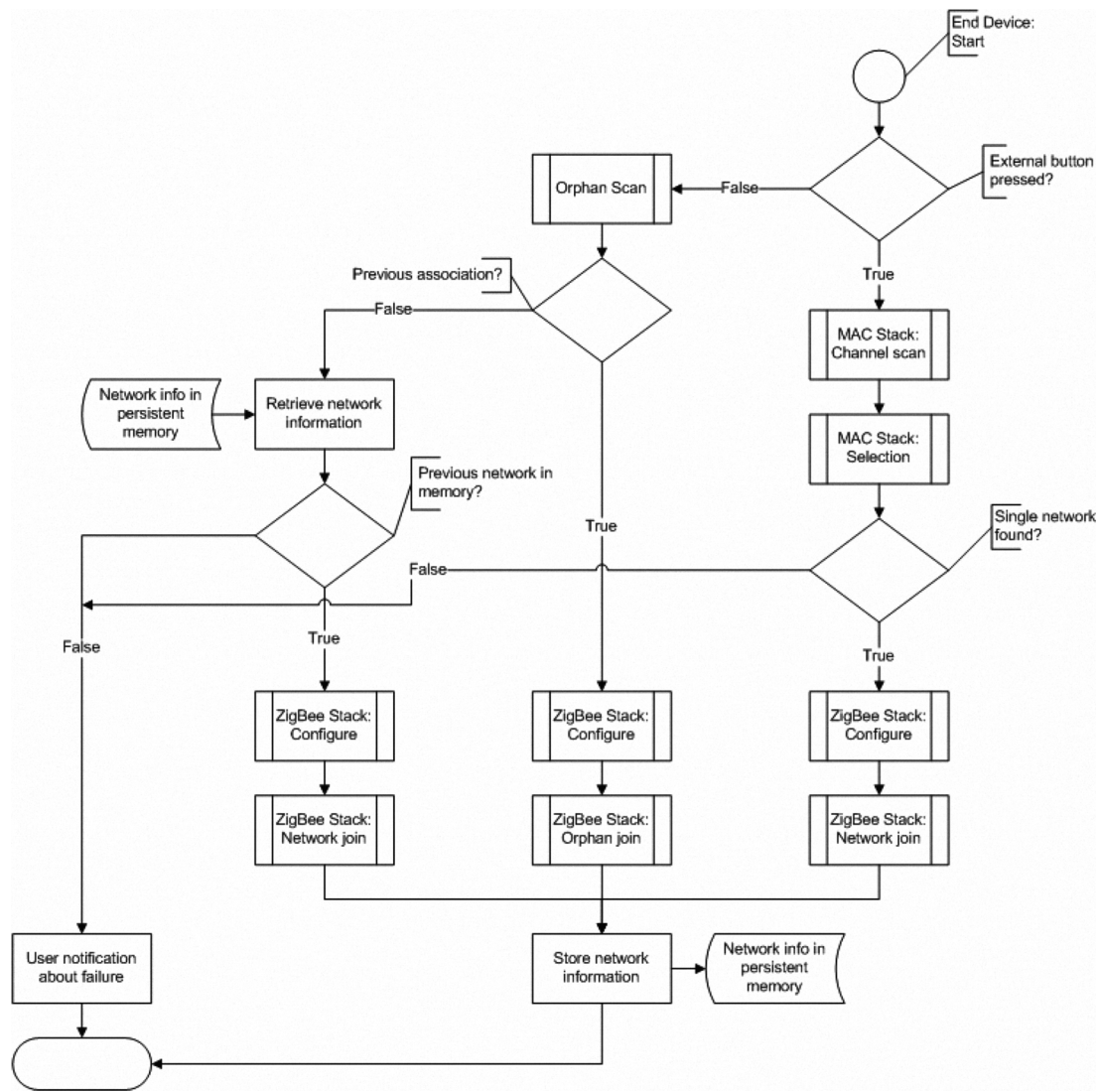


Fig. 5. End Device start procedure.

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