WiEnum: Node Enumeration in Wireless Networks

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***Abstract*—Assigning unique consecutive numerical identifiers (IDs) to the nodes of a multi-hop wireless network is an important problem, as it enables critical functions such as resource distribution (e.g., TDMA time slots) and leader election. If also used as a mean to "shorten" otherwise assigned node IDs node enumeration saves energy and imposes lower complexity. In this paper we present an efficient scheme for enumerating the N nodes of a multi-hop wireless network. Our protocol, called WiEnum for Wireless Enumeration, is distributed and, by means of the sole exchange of packets among neighbors, terminates with each node having a unique ID in the range 1 to N. Through Castalia-based simulations we demonstrate the effectiveness of WiEnum in assigning unique, short IDs by comparing its performance to that of another leading algorithm for ID assignments, termed SIDA. Our results show that, in terms of completion time (i.e., the time it takes till each node gets its unique ID) WiEnum outperforms SIDA, especially in networks with higher number of nodes and density. At the same time, WiEnum keeps energy consumption to levels that are always lower than those of SIDA.**

I. Introduction

Multi-hop wireless networks, sometimes referred to as MANETs or Ad Hoc Networks [1], are a communication paradigm that has found myriads of applications in different fields, ranging from vehicular communications VANETs [2], underwater networking [3], and wireless sensor networks (WSNs) [4]. Since wireless nodes are typically battery powered, these networks necessitate a suitable degree of energy efficiency in their operations, especially those concerning data transmission. Nodes transmit packets of data to each other. These packets, typically, are made up of a header that contains information pertinent to the nodes that are communicating, and the payload, which contains the data being transmitted. In the packet headers, the nodes—usually the source and the destination of the packet—are represented by unique identifiers (IDs).

In wireless networks, the uniqueness of a node ID can be guaranteed, for instance, by choosing as node ID the MAC address of its wireless network interface card. This, however, can sensibly affect energy consumption, as these addresses are 48 bits long. In networks such as WSNs, where nodes may use wireless technologies with short, fixed-size packet (e.g., 36 bytes, as for some commercial motes [5]), using 12 bytes just for addressing purposes imposes quite the overhead on communication, leaving a limited number of bytes for the payload. Furthermore, relevant problems for wireless networks, including enabling collision-free inter-node communication via Time Division Multiple Access (TDMA) and leader election, are not best solved by using MAC addresses, as they are not consecutive and the gap between any two MAC IDs of network nodes is unpredictable.

Finding a way of "shortening" node IDs, i.e., assigning nodes with unique strings of bits that are considerably shorter than MAC addresses, is therefore an important problem for wireless networking. Solutions to this problem have been proposed that, as requested by the nature or multi-hop wireless networks, are primarily distributed protocols striving to minimize energy consumption. The aim is that of defining assignment schemes that, although generating some overhead for determining node IDs, produce IDs that, in the long run, significantly reduce the overall network energy consumption, and enable useful operations more efficiently. A review of solutions to this problem is provided in Section IV.

In this paper we contribute to the problem of determining short IDs for the nodes of a multi-hop wireless network by proposing a new protocol that assigns each node with a fixed-length ID whose size is logarithmic in the network size. In particular, given a networks with N nodes, our protocol *enumerates* the node of the networks, i.e., assigns to each one of them a unique number in the range 1 through N. The protocol, termed WiEnum for Wireless Enumeration, is based on the local exchange of "ID packets" among neighbors, thus being distributed and localized. These packets contain lists of nodes with their selected IDs. As the packet exchange proceeds, each node maintains a list of all the nodes and IDs, i.e., keeps track of the progress of the ID assignment process (progress view). Neighboring nodes reach a consensus on which ID they choose by cross referencing their progress views: If multiple nodes have the same ID, actions are taken to change conflicting IDs and the new assignment is communicated to the neighbors. Eventually, each node will have a view that reflects the state of the entire network. Once every ID on the list is unique, the protocol is complete. We note that, besides producing reasonably short ID (remarkably shorter than MAC addresses for networks with up to several thousands of nodes), solutions to problems such as TDMA time slot assignment and leader election are immediate byproducts of our protocol.

We demonstrate the effectiveness of WiEnum in producing unique, consecutive short IDs by evaluating its performance when run on networks whose operations demand energy efficiency, namely, wireless sensor networks (WSNs). The performance of WiEnum is compared to that of another protocols for unique ID assignment in WSNs, termed SIDA [5]. Besides being the best performing protocol proposed so far

978-1-5090-0073-9/15/$31.00 ©2015 IEEE

for this problem, SIDA also represents a different approach to performing ID assignment. In particular, it produces unique IDs of *variable length* in the range 1 through N by building a spanning tree rooted at the WSN data collection node (the sink). We implemented WiEnum and SIDA in Castalia [6], a freely available network simulator particularly geared towards wireless sensor networking, modeling energy consumption, as well as MAC and physical layer aspects of WSNs realistically. In scenarios of networks with increasing size and density, we investigate the two key metrics of completion time (i.e., the time it takes for all nodes to be assigned a unique ID) and energy consumption per node. Our results show that WiEnum clearly outperforms SIDA in terms of completion time. Especially in WSN with a large number of nodes ($N = 200$) and with high density (average number of neighbors per node > 25), we observe that WiEnum terminates the ID assignment process in a half of the time needed by SIDA to terminate. Energy consumption is also kept at bay, and nodes running WiEnum spend less or the same energy of the other protocol.

The remainder of the paper is organized as follows. In Section II we introduce WiEnum in detail. Section III illustrates the comparative performance evaluation of WiEnum and SIDA on WSN scenarios: The experimental setup is introduced, metrics of interest are defined, and simulation results are shown and discussed. Section IV summarized previous works on unique short ID assignment and enumeration protocols for wireless networks. Finally, Section V concludes the paper.

II. Protocol Description

WiEnum is described by using the following notation.

- The set V is the set of the $N = |V|$ nodes in the network. We assume that N is known to all nodes v in the network.[1]
- For each $v \in V$, $ID(v)$ indicates v unique identifier. This can be any number, in any suitable base. We assume that each node v knows $ID(v)$.
- With $n(v)$ we indicate the unique number that a node $v \in V$ assumes by the end of WiEnum, $1 \leq n(v) \leq N$.
- The *progress view* $P(v)$ stores a node v current view of the enumeration progress, i.e., the set of pairs $(ID(u), n(u))$ received so far from its neighbors.
- By **transmit** $\langle m \rangle$ we intend that a node broadcasts a packet whose payload is m. We assume that these packets are correctly delivered to all the neighbors of the sender by a finite, yet unpredictable, time. Communications are asynchronous, i.e., nodes are not supposed to be synchronized and broadcast their packets as soon as the protocol generates them.

The protocol is executed at each node v in V. Upon starting its operations, node v executes the following initialization procedure *InitEnum* (Algorithm 1).[2]

Algorithm 1 *InitEnum*() (executed by node v upon starting its operations)

$n(v) = 1$
$P(v) = \{(ID(v),\, n(v))\}$
transmit $\langle P(v) \rangle$

Each node v initially gets the value 1 and initializes its set $P(v)$ to its own current view, i.e., to the pair $(ID(v), n(v))$. It is now ready to share its view of the enumeration progress to its neighbors, and therefore broadcasts $\langle P(v) \rangle$.

The rest of the algorithm is triggered by the reception of a packet containing $\langle P(u) \rangle$ from a neighbor u, as detailed in the following Algorithm 2, *ReceiveProgress*.

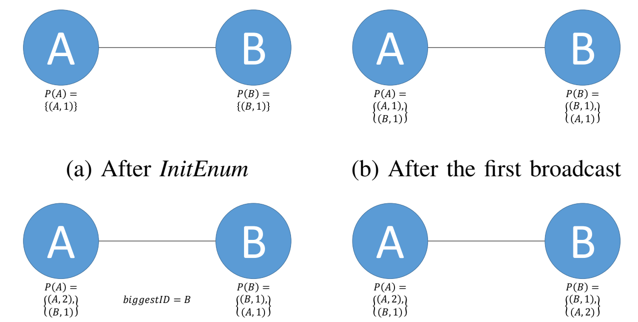
Algorithm 2 *ReceiveProgress*($\langle P(u) \rangle$) (executed by node v upon receiving $\langle P(u) \rangle$ from a neighbor u)

$P(v) =$ *MergeProgress*$(P(v), P(u))$
$sameValIDSet = \{z \in P(v) : z \neq v \wedge n(z) = n(v)\}$
if $sameValIDSet \neq \emptyset$ **then**
  $biggestID = \max(ID(z) : z \in sameValIDSet)$
  if $ID(v) < biggestID$ **then**
    $n(v) = \max(n(z) : z \in P(v)) + 1$
    $P(v) =$ *MergeProgress*$(P(v), \{ID(v), n(v)\})$
if $P(v)$ has changed **then**
  transmit $\langle P(v) \rangle$
if $|P(v)| = N \wedge \forall u, z \in V : n(u) \neq n(z)$ **then**
  EXIT

Node v merges its local view with the local view just received from node u. To this purpose it uses the function *MergeProgress* that given two progress views returns a progress view where, in case there are multiple pairs with the same first element, e.g., $(ID(z), n_1(z))$, $(ID(z), n_2(z))$, $\ldots$, $(ID(z), n_k(z))$, $k \leq N$ and $z \in V$, only one is retained: The one with the biggest value among $n_i(z)$, $1 \leq i \leq k$. A new set $sameValIDSet$ is then created with all those nodes $z \in V$ different from v, if any, such that $(ID(z), n(z)) \in P(v)$ and $n(z)$ is the same value chosen so far by v. If there is at least one of such nodes, v has to decide whether to change its own $n(v)$, since all numbers must be unique. To this purpose, the biggest ID among the nodes in $sameValIDSet$ is selected and compared to that of node v. If the ID of v is smaller, then v proceeds to change its current value, and it sets it to the biggest value it has seen so far increased by 1. Its progress view is updated accordingly. If during the procedure the progress view of node v is changed, v broadcast its new view of the progress to its neighbors. Finally, node v verifies whether all the nodes

[1] This assumption can be relaxed at the cost of applying schemes for determining the size of a multi-hop wireless network [7].

[2] It is unlikely that all the nodes will start the execution of the protocol, or in general, that they will be “turned on” all at the same time. It is however realistic to assume that all nodes are up and running within a limited amount of time from when the first node comes alive. Furthermore, although customary in many wireless network applications, in this case it is not necessary that each node becomes aware of the identity and number of its neighbors. This might be useful, however, when exchange of packets at the MAC layer is implemented through one-to-one communication.



(a) After *InitEnum*

(b) After the first broadcast

(c) The progress views are modified based on biggest ID

(d) After the second broadcast

Fig. 1: WiEnum: A simple example.

have received their own unique values, and if this is the case, node v exits the execution of the enumeration algorithm.

Since the termination conditions for the algorithm require that each node have a unique integer identifier, and the allowed integer identifiers are in the range $[1, N]$, in the case of network with connected topologies (i.e., no isolated nodes, etc.) and assuming a MAC layer that always delivers packets, if the algorithm terminates, it is guaranteed to terminate correctly. (A detailed proof of correctness will be given in an expanded version of this paper.)

Fig. 1 illustrate the operations of WiEnum in a sample network with just two nodes. Fig. 1a depicts the initial state of the network, after both nodes just started the protocol. Fig. 1b depicts the state of the network after the nodes have received each other progress views. In Fig. 1c the nodes determine the biggest ID. Assuming $B > A$, node A modifies its progress view. Finally, Fig. 1d shows the state of the nodes after they have received each other progress views again, causing node B to update its progress view. At this point, the network is fully enumerated, and the protocol terminates.

III. Performance Evaluation

A. Simulation scenarios and settings

We implement WiEnum in Castalia, a freely available sensor network simulator commonly used to model runtime and energy related aspects of wireless sensor networks [6]. Castalia provides a channel/radio model for data-link, network, and transport layers of typical WSN protocol stacks. It also provides a set of tunable parameters for the physical layer of a sensor node. In our simulations we use the CC2420-based radio hardware model of the TelosB mote, which is IEEE 802.15.4 compliant. The MAC layer is modeled after the TinyOS implementation of the CC2420 MAC [8]. Packet collisions are determined based on the additive interference model, according to which simultaneous transmissions from multiple nodes are calculated as interference at the receiver, by linearly adding their effect. The maximum packet size is 128 bytes, as from the IEEE 802.15.4 specifications [9]. The channel data rate is set to 250kbs per second. The transmission

TABLE I: Simulation parameters.

Parameter	Value
Radio hardware	CC2420-based
MAC	IEEE 802.15.4 compliant
Packet size	128B
Data rate	250Kbps
Transmission power	58.5mW
Reception power	65.4mW
Transmission range	70m
Length of node unique ID	16 bits (IEEE 802.15.4)
Simulation area	300m $\times$300m
Number of nodes N	$25, 50, 75, \ldots, 200$

and reception power are set to 58.5mW and to 65.4mW, respectively, as for the TelosB mote [10]. We assume that when not transmitting or receiving packets, node radios are in sleep mode, i.e., consume negligible energy (we can use an on-board wake-up low-power radio receiver like that presented in [11]). The transmission range is set to 70m. Finally, the length of a node unique ID is set to 16 bits, which is one of the options provided by the IEEE 802.15.4 specifications [9]. All nodes start their operation within a short interval of time.

We consider connected networks with N nodes, randomly and uniformly scattered in a square area of size 300m $\times$300m. The network size N is varied in $\{25, 50, 75, \ldots, 200\}$. The topologies so obtained have nodes whose average number of neighbors (density) varies from 3.6 ($N = 25$) to 27.5 ($N = 200$), thus providing insights on the protocol operations on sparse to very dense WSNs. Table I summarizes the simulation parameters.

The performance of WiEnum is compared to that of SIDA, for the details of which we refer the reader to the paper by Lin et al. [5], where it was originally proposed. A brief description is provided in Section IV.

For each value of the network size N we generate 1000 connected topologies, and execute WiEnum and SIDA on each. This obtains us results with a 95% confidence interval and a 5% precision.

B. Performance metrics

We compare the performance of WiEnum and SIDA with respect to the following metrics:

1) *Completion time*. This is the average time it takes to complete the enumeration protocol, measured as the time from when the last node starts the protocol itself to the time when every node has its unique ID.
2) *Energy consumption per node*. We calculate the mean energy consumed by each node for protocol execution. The energy needed for transmission and reception is determined by counting the bytes of the WiEnum packet, the MAC layer overhead and the overhead from the physical layer. This byte count is then multiplied by the average power needed for transmission and reception and the time it take to transmit or receive those bytes. We calculate the energy consumption for the entire network and divide it by the number of nodes.

C. Performance results

Simulation results for the average completion time and the average energy consumption per node are shown in Fig. 2 and Fig. 3, respectively.

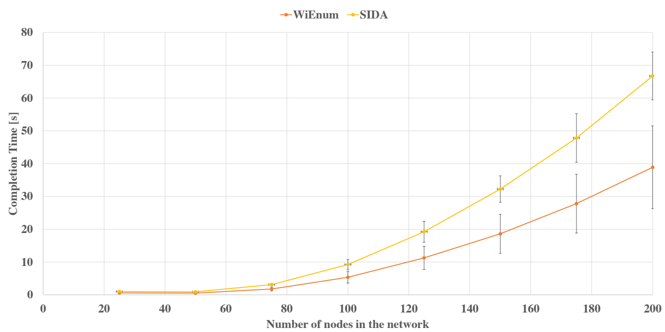


Fig. 2: Completion time.

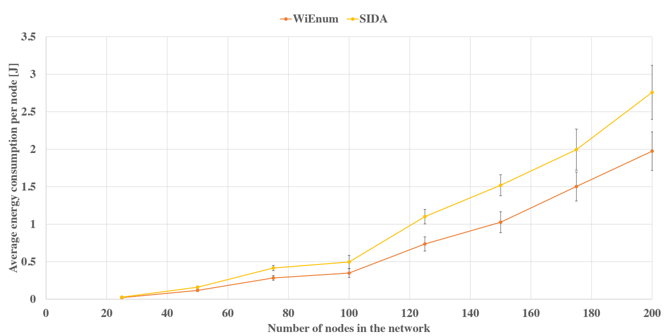


Fig. 3: Energy consumption per node.

In general, we observe that independently of the protocol, significantly more time and energy are needed for ID assignment in larger networks. This is expected, as larger networks imply a larger number of neighbors per node and larger average packet size, which detrimentally affect the number of collisions and re-transmissions, thus imposing longer times and demanding more energy. More specifically, we observe the following.

Completion time. Compared to SIDA, WiEnum is significantly faster (Fig. 2). Irrespective of network size, the completion time of SIDA is always higher than that of WiEnum. This is due to the three construction process in SIDA, which is a "network wide" operation rather than a local one. Besides imposing longer times, building a tree induces extra overhead and suffers a higher amount of packet collisions, which in turn requires extra time for a packet to get through to its recipients. Overall, the localized nature of the packet exchange of WiEnum has a very beneficial effect on the time it takes to complete the enumeration process.

Energy consumption per node. As shown in Fig. 3, the average energy consumption per node of SIDA consistently remains higher than that of WiEnum. In general, especially for networks with over 75 nodes, it keeps being at least 10% more than the energy consumption per node incurred by WiEnum. As the networks size becomes large ($N \geq 100$), we observe that the energy consumed by WiEnum is sensitive to network density.

IV. Related Works

Research on short unique ID assignment/network enumeration for wireless networks has produced studies approaching the problem from different angles. A number of algorithms have been proposed for theoretical models, to establish a mathematical basis for this research. Several applied solutions for short ID assignment protocols have also been proposed and modeled, focusing on how the short unique ID assignment affects the energy consumption of the energy constrained networks such as WSNs. Finally, various short unique ID assignment protocols have been investigated, and their performances have been compared in different studies. These investigations provide useful information for understanding how short unique ID assignment schemes operate, as well as provide a perspective of the various scenarios and issues that are commonly encountered.

A number of papers propose algorithms for reducing the length of a node ID. These algorithms use address encoding, local ID assignment, and other techniques. For example, Schurgers et al. propose an on-demand MAC address assignment scheme that reuses spatial addresses and encodes address representation [12]. The algorithm is distributed, and the resulting address size and energy savings scale well with network size. Chae et al. propose schemes for ID assignment, mobility management, and power saving for WSNs [13]. This set of protocols is used to improve the energy efficiency of WSN operation, while allowing for a dynamic network topology. Ali et al. propose an energy-efficient short address naming scheme that uses a clustering routing approach [14]. Kang et al. propose a structure-based algorithm to assign locally unique IDs to nodes in a WSN [15]. This algorithm uses a group-and-search scheme on a grid layout to minimize the energy consumption of ID assignment. Liu et al. propose the GREENWIS local ID assignment scheme, which uses semi-roaming routing and node location information to generate 5-tuple unique IDs within an application field [16].

Some studies evaluate and comparing existing algorithms. Uddin et al. evaluate and compares addressing techniques for wireless sensor networks [17]. The paper classifies addressing techniques by their schemes, and evaluated the protocols with respect to the objectives of each scheme. The investigation then compares the schemes and their trade-offs. Challa et al. exhaustively contrast two categories of short ID assignment protocols [18]. Multiple proactive and reactive ID assignment schemes are compared in terms of completion time, energy consumption, communication overhead and packet size.

Papers are proposed that look at the effects of protocol framework and network topology. Pan et al. evaluate the properties of WSN topologies, and define the "long-thin" (LT) class of network topologies [19]. They then show how this topology is not conducive to address assignment using the ZigBee tree-routing scheme. Finally, they propose a new address assignment and routing scheme that works well for LT networks. Evers et al. propose a number of algorithms to determine the number of nodes in a wireless network by counting the immediate neighbors of each node [7]. The algorithms are developed using an analytic approach from graph theory, and are then implemented and compared. Ryu et al. investigate a set of enumeration algorithms as applied to graphs representing WSN topologies [20]. The paper evaluates ID swapping and simulated annealing algorithms, looking at both centralized and decentralized approaches.

A number of studies propose schemes that can assign global enumerated IDs to the nodes of a wireless network. Ribeiro et al. propose an assignment protocol that uses negative acknowledgments and flood control to minimize energy consumption [21]. This protocol also handles communication security, as well as dynamic network modifications such as network fusions and partitions. Mazurkiewicz [22] proposes an algorithm for distributed enumeration in a graph. (WiEnum is based on this original idea, which is however, highly theoretical and described for anonymous graphs, i.e., graph where nodes have no unique ID.) Zhou et al. propose a reactive ID assignment protocol that works with a directed-diffusion communication paradigm to assign locally unique IDs while minimizing communication overhead, thereby improving energy efficiency [23]. Ould-Ahmed-Vall et al. propose a proactive distributed algorithm for generating a tree overlay and assigning globally unique IDs using the tree [24].

A special mention goes to the two following protocols, whose performance we choose to compare to that of WiEnum. SIDA, for Self-organized ID Assignment, is a global ID assignment protocol proposed by Lin et al. [5]. It is fully localized and produces variable length IDs for WSNs whose nodes (and size) can change in time. SIDA starts by builds a binary tree overlay on the wireless network topology, and then uses the depth of each node in the tree to generate a Huffman coding-based ID for each node such that nodes further away from the sink have shorter IDs than nodes closer to the sink. SIDA is shown to perform well with regards to scalability, flexibility, and energy efficiency compared to previous solutions. Zheng et al. propose the Energy Efficient Clustering Self-Organized ID Assignment (EECSIA) [25]. This protocol implements local unique ID assignment based on a clustering structure imposed on the network topology. Clusterheads are selected based on network density and node residual energy, and assign locally unique IDs to nodes in their clusters. Global uniqueness of the IDs is then obtained via the cluster hierarchy.

V. Conclusions

This paper introduces WiEnum, a new unique ID assignment protocol for multi-hop wireless networks. Specifically, WiEnum gives each of the N nodes of the network an integer ID in the range 1 through N. The performance of WiEnum is evaluated via Castalia-based simulations over randomly generated topologies of wireless sensor networks scenarios. In particular, we investigated the time it takes to the protocols to complete the ID assignment process, and the energy consumed by each node for it. The performance of WiEnum is compared to that of another protocol for short ID assignment, namely, SIDA. Our results show that our protocol produces network enumerations considerably faster than the previous solution, while requiring the same amount of energy or less.

Future directions of our work include the evaluation of the energy savings produced by using our ID as addresses for routing, as well as investigating ways of making WiEnum more scalable, possibly in conjunction with a clustering scheme. We also intend to investigate the performance of WiEnum in more dynamic scenarios, where nodes are added and removed to/from the network.

Acknowledgments

This work was supported in part by the US National Science Foundation under research grant CNS-1143681.

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