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Lease based Addressing for Event-Driven Wireless Sensor Networks

R. Chellappa Doss, D. Chandra, L. Pan, W.Zhou, M. Chowdhury
School of Engineering and Information Technology
Deakin Univeristy, 221 Burwood Hwy, Victoria 3125, Australia.
{rchell, dchandra, ln, wanlei, muc}@deakin.edu.au

Abstract

Sensor Networks have applications in diverse fields. They can be deployed for habitat modeling, temperature monitoring and industrial sensing. They also find applications in battlefield awareness and emergency (first) response situations. While unique addressing is not a requirement of many data collecting applications of wireless sensor networks it is vital for the success of applications such as emergency response. Data that cannot be associated with a specific node becomes useless in such situations. In this work we propose an addressing mechanism for event-driven wireless sensor networks. The proposed scheme eliminates the need for network wide Duplicate Address Detection (DAD) and enables reuse of addresses.

Keywords – Wireless Sensors, System Design, Simulations, Network Measurements.

1. Introduction

Wireless sensor networks (WSNs) are self-organizing networks that do not depend on a fixed communication infrastructure. This makes them ad hoc networks that can be easily deployed in minimum time. They are composed of a large number of sensing devices (sensors) designed to sense and collect data of particular interest. The sensors are low-cost, low-power devices that have limited computational and communication capabilities. These limitations introduce challenges to protocol development, application design and information security.

Sensor Networks have applications in diverse fields. They. An application that has become increasingly attractive in the post 9/11 era is the use of wireless sensor networks for emergency (first) response in mass casualty incidents. It is envisioned that these networks will play a pivotal role in disaster response and recovery [1].

Wireless sensor network applications can be categorized as either data-centric or node-centric applications. While both categories of applications are concerned with data monitoring/collecting, data-centric applications do not require the node of data generation to be uniquely identified. An example of a data-centric application is a temperature monitoring application. Node-centric applications however require the identity of the node of data generation to be preserved. In such applications data that is collected becomes useless if the source (sensor node) cannot be identified. This implies that in such applications each node should be uniquely identifiable. An example is vital sign monitoring in emergency response [1] [2].

Two levels of information can be identified in sensor nodes – events and data. Events are defined as critical data that is generated by a node [6] (e.g., a patient's vital sign measurement falls below a critical threshold or enemy movement has been detected). In event-driven sensor networks only events are of interest and need to be communicated to the sink. As is readily obvious the sensors generating the events need to be uniquely identified.

In this work we propose an On-demand lease based addressing mechanism that can guarantee network level uniqueness. The scheme is suited for event-driven sensor networks and reuses addresses efficiently. It is also energy-efficient as it eliminates the need for Duplicate Address Detection (DAD). In section II we present related work followed by our proposed scheme in Section III. Analysis of the scheme is presented in Section IV followed by simulation results validating the effectiveness of the scheme in Section V. We conclude with final comments in Section VI.

2. Related Work

Traditionally each node is assigned a network level address (such as an IP address) and a link level address (or MAC). Both these addresses are globally unique and hence the address space tends to be quite large.

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The amount of data (payload) carried in each Internet packet is comparatively large which compensates for this overhead. However, the data rate of sensor nodes is often as low as 16 bits per packet [3] which makes it impractical to introduce such high addressing overheads. Furthermore, with the need for energy efficiency it is imperative to minimize the control overhead. The need for efficient addressing schemes is well articulated with various addressing schemes proposed in literature [3] [6] [7] [8] [9]. Addressing schemes proposed for sensor networks can be broadly categorized as 'Stateful' approaches that makes use of an address allocation table, and 'Stateless' approaches that do not use allocation tables [11]. While stateless approaches are less complex, they employ network-wide Duplicate Address Detection (DAD) to ensure uniqueness of addresses. Since DAD messages are broadcast they often result in high overheads and increase the latency of address assignment.

In [3] an energy-efficient node address naming scheme using spatial reuse of locally unique addresses is presented. Nodes are organized in a hierarchy of logical layers and the layer numbers are used to satisfy the uniqueness condition. TreeCast [5] is a stateless addressing scheme proposed for efficient addressing. It requires the construction of multiple disjoint trees that are intertwined and rooted at the sink. A similar scheme [8] is based on the concept of hierarchical levels and repeated patterns and supports self-organization in sensor networks. In [4] a distributed on-demand addressing mechanism is proposed for assignment of MAC addresses. Event-driven addressing has been proposed in [7]. Local uniqueness between immediate neighbors is aimed for with link level addressing, while an on-demand mechanism for network level addressing is proposed. The addressing protocol is coupled with the routing protocol and employs Duplicate Address Detection (DAD) that is centered on each node that has detected an event to ensure network level uniqueness. Since DAD is a broadcast based mechanism, the overhead of addressing will tend to be quite significant in large scale sensor networks. In [6], data aggregation and dilution by modulus addressing is proposed. An addressing mechanism based on a hierarchical architecture and where the nodes are interconnected making use of a de Bruijn graph is also proposed [9].

All of the above addressing schemes place the complexity of the addressing process on the sensor nodes by insisting on strict organization or by DAD through flooding. In our work the complexity is removed from the sensor nodes to the network control centre (sink).

3. Lease based Addressing for WSNs

The proposed addressing mechanism is an on-demand addressing protocol that employs a lease-based approach for address assignment. It exploits the random nature of event occurrence in event-driven sensor networks. Addresses are assigned and released in a dynamic manner enabling reuse. In large scale sensor networks such an approach can reduce the overhead of addressing quite significantly.

Location awareness is a requirement of many WSN applications [7]. In most applications data that cannot be tied down to a location is useless. The proposed mechanism incorporates location awareness and works with both absolute and relative levels of awareness.

The proposed addressing scheme has the following three phases – Boot up phase, Address Request Phase and Address release phase.

3.1 Boot Up Phase

The dynamic addressing mechanism is used only for assignment of network level addressing. During the boot up phase each node self-assigns a local link-level address that is locally unique. The assignment of the link-level address proceeds along similar lines as described in [7]. The link-level address is assigned permanently to the node and is only reassigned in the event of the original node dying. When new nodes join the network they self-assign a local link level address on boot up. During boot up, the Sink (S) broadcasts a configuration packet, that contains the location of the sink (*x* & *y* co-ordinates). The purpose of this configuration packet is to allow each of the sensor nodes to calculate their distances from the sink. A sensor node is deemed to have successfully joined the network (booted) only after the reception of this configuration packet. The distance of the sensor node from the sink, $d_{i,SINK}$ is calculated according to (1). Since the sensor nodes are relatively stationary, recalculation of the distance is not required after boot up. Each sensor node is assumed to be connected to a location device such as a GPS receiver. The use of the location device is only required during the boot up phase thus ensuring that the scheme remains energy-efficient.

$$d_{i,SINK} = \sqrt{(x_{SINK} - x_i)^2 - (y_{SINK} - y_i)^2} . \quad (1)$$

Alternate boot up procedures based on parent nodes and tree-based routing can also be used. In this work we use a simple distance based rule for the forwarding of the address request from the requesting sensor node to the sink.

3.2 Address Request Phase

Once a node has successfully completed the boot up phase it becomes a candidate for address request. A node performs its data monitoring function with limited levels of local processing to generate an event. An event is deemed to occur when the data crosses a pre-defined threshold. In order for the event to be communicated reliably to the sink a network level address is required to identify the source of the event at the sink (link-level addresses are only locally unique). The node generates an address request packet of the form {*Source, Destination, Type, event_ID, moteDist, X pos, Y pos*}. The address request packet carries an *event_ID* (that is generated using a random function that takes the link level address as an input) to uniquely identify the address request and to match the corresponding reply (address allocation) from the sink to the original address request. The sink maintains an address allocation table with a list of addresses and a corresponding status flag for each address indicating whether the address is free or has been allocated. On the receipt of an address request the sink allocates a free address to the requesting node based on availability or alternatively discards the address request. The sink has the option to queue the address requests. Each individual sensor node also has the option of retransmitting the address request after a pre-defined time interval. In our simulations for the sake of simplicity address requests are not queued at the sink or retransmitted by individual sensor nodes. Forwarding of the address request from the sensor node to the sink is done making use of limited scope flooding. This is achieved making use of the distance rule.

We define the distance rule to be – a node i forwards an address request from node j only if it is closer to the sink than node j (i.e., the forwarding node to it). The distance rule has been previously used in location aided routing protocols [11] for mobile ad hoc networks and is shown to be an effective mechanism. On the receipt of the address request packet the sink responds with an address allocation packet of the form {*Source, Type, event_ID, moteDist, Address, X pos, Y pos*}. The event_ID is copied to the allocation packet as stated earlier. Limited scope flooding using the distance rule is again employed to forward the reply to the requesting node. However distance calculations are with respect to the destination sensor. This requires that the location information of the final destination sensor is included in the reply message generated by the sink.

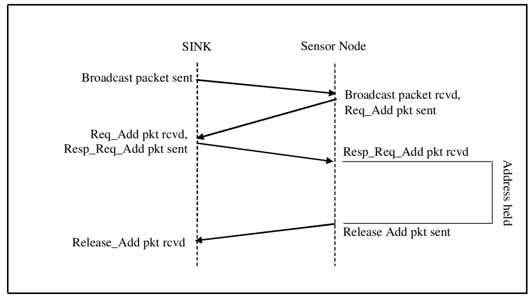

Figure 1 Request, Allocation and Release

3.3. Address Release Phase

To enable reuse of addresses and optimization of the size of the address space, addresses are not allocated on a permanent basis to each sensor node. Instead, we adopt a lease based approach. Each address is allocated to a sensor for a period of time defined as a lease. On the expiry of the lease the address is released and is free to be allocated to another sensor node. The success of lease based schemes depends on the effectiveness of the lease management mechanism. We adopt a node-based lease management mechanism for our scheme. While it can be argued that a sink based scheme is preferred to reduce the computation, we believe that in event-driven networks a node-based approach is more beneficial. Such an approach allows the node to release the address once communication relating to the event has been completed. When a node decides to release an address it sends a release message of the form {*Source, Destination, Type, moteDist, Release_Address*} to the sink. The sink deallocates the specific address which allows for the address to be reused by other nodes in the network. The release of the address is controlled entirely by the sensor nodes while the address allocation is controlled entirely by the sink nodes. The advantage of centralised address allocation controlled at the sink is that DAD can now be done at a central point. In comparison, other schemes perform DAD by flooding the entire network to see if a duplicate address exists across the network. Figure 1 illustrates address request, allocation and release.

4. Probability of Address Allocation

According to the lease based addressing scheme, each sink either issues an address or replies with a denial of address request to a sensor. A sink always issues an address to the sensor upon receipt of a request, if there is at least one address available in the sink; otherwise, the sink denies a request as there is no available address. Hence we could construct a state machine for the sink consisting of two states - state “1” guarantees the address allocation and state "0" means denial of request. Two transitive actions (Last Allocation with possibility λ and Address Return with possibility μ) are associated with these two states as in Figure 2.

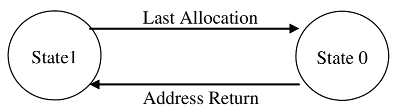

Figure 2 Transitive actions in the Sink

According to the definition of Markov Chain [12], the above state machine gives us the following equation of the probability function set *P(t)* (state 1 and state 0 have $P_1(t)$ and $P_0(t)$ respectively) and the transition matrix *Q(t)*:

$$P'(t) = P(t) \times Q(t) \tag{2}$$

Where $P(t) = \left[P_1(t), P_0(t)\right]$ and

$$Q(t) = \begin{bmatrix} -\lambda & \lambda \\ \mu & -\mu \end{bmatrix} \tag{3}$$

After matrix multiplication we get:

$$\begin{cases} P_1'(t) = -\lambda \cdot P_1(t) + \mu \cdot P_0(t) \\ P_0'(t) = \lambda \cdot P_1(t) - \mu \cdot P_0(t) \end{cases} \tag{4}$$

The sink either issues an address or denies the request, which indicates $P_1(t) + P_0(t) = 1$ at any given time *t*. At the initial moment $t = 0$, the sink is always able to allocate an address, so $P_1(0) = 1$. We substitute $P_0(t)$ with $1 - P_1(t)$, so we have:

$$P_1'(t) + (\lambda + \mu) \cdot P_1(t) = \mu \tag{5}$$

Solving this differential equation, we will get the solution for the possibility of successfully acquiring and address from the sink

$$\begin{aligned} P_1(t) &= \frac{\mu}{\lambda+\mu}\left(1 - e^{-(\lambda+\mu)\cdot t}\right) + P_1(0) \cdot e^{-(\lambda+\mu)\cdot t} \\ &= \frac{\mu}{\lambda+\mu}\left(1 - e^{-(\lambda+\mu)\cdot t}\right) + e^{-(\lambda+\mu)\cdot t} \\ &= \frac{\mu}{\lambda+\mu} + \frac{\lambda}{\lambda+\mu} e^{-(\lambda+\mu)\cdot t} \end{aligned} \tag{6}$$

When *t* approaches infinity, we can derive the probability of successfully acquiring an address from the sink, which is

$$\lim_{t\to\infty} P_1(t) = \lim_{t\to\infty}\left(\frac{\mu}{\lambda+\mu} + \frac{\lambda}{\lambda+\mu} e^{-(\lambda+\mu)\cdot t}\right) = \frac{\mu}{\lambda+\mu} \tag{7}$$

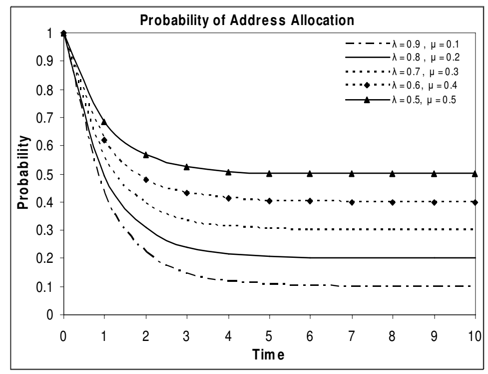

Figure 3 Data plot of function $P_1(t)$

Figure 3 denotes the probability of address allocation. According to the definition of our protocol, each sensor could hold an address for a random time in the range of $[t_{\min}, t_{\max}]$. So each active sensor *i*, has $1/t_i$ possibility to return the address, where t_i is the time an address was held. Since there are maximally n active sensors (size of the address space), the address return possibility μ is the sum of the returning possibility $\sum_{i=1}^{n} 1/t_i$, which gives a range of $\left[\frac{1}{t_{\max}}, \frac{n}{t_{\min}}\right]$

Similarly, the address allocation possibility λ is determined by the number of sensors making address requests and the frequency of requests. Suppose we have N events in total and each sensor that detects an event requests for an address every $T \in [T_{\min}, T_{\max}]$ seconds, λ is the sum of the requesting possibility $\sum_{i=1}^{N-n} \frac{1}{T_i}$, which gives a range of $\left[\frac{1}{T_{\max}}, \frac{N-n}{T_{\min}}\right]$.

According to the previous derivation, the success probability of acquiring an address approaches a constant determined by λ and μ as time increases. Furthermore, we could easily show that the probability increases as the ratio of μ/λ increases, and decreases when that ratio drops. With the change of λ and μ, the ratio of μ/λ has a range of:

$$\left[\frac{\mu_{\min}}{\lambda_{\max}}, \frac{\mu_{\max}}{\lambda_{\min}}\right] = \left[\frac{T_{\min}}{(N-n)\cdot t_{\max}}, \frac{n \cdot T_{\max}}{t_{\min}}\right] \tag{8}$$

5. Simulation Results

Performance evaluation of the proposed lease based address allocation scheme was completed making use of OPNET modeler 11.0. In order to evaluate the lease based addressing scheme and the different phases of the scheme we define three metrics of interest

Percentage of Successful Boots: As the scheme relies heavily on the location information of the sink it is vital that in evaluation of the address allocation and address release phases we are informed of the performance of the boot phase of the scheme. We calculate the percentage of successful boots that have successfully received a boot packet from the sink as well as obtained a link level address that is locally unique.

Percentage of Satisfied Requests: This metric gives us an idea of the level of address reuse achieved by the lease based scheme. This is the long run fraction over time of the total number of address requests received at the sink and the number of address allocations. The number of address allocations performed is limited by size of the address space and the frequency of address release.

Delay in address allocation: This metric gives us an idea of the delay experienced by a node from the time it requests for an address to the time it successfully obtains an address. Only successful address allocations are included in our initial evaluations.

Simulation study was conducted by deploying wireless sensors in an area of 1000m by 1000m. All deployments were done making use of random seeds which was aimed at replicating real-world deployments such as scattering of wireless sensors over the field of interest using unmanned aerial vehicles (UAV). Each sensor node had a communication range of 150 m. We considered 7 deployments of 150, 200, 250, 300, 350, 400 and 450 nodes for performance evaluation. Delay measurements were completed making use of smaller deployments (20-100 nodes). Each simulation run was for 600 secs with event generation starting after the first 30 secs of each run. This 30 sec period was allocated for boot up and all sensors that were successful in this phase were capable of generating events. Each node generated an event at a random time specified by a random function and bounded by [t_{min}, t_{max}]. In our simulations t_{min} was set to 30 secs and t_{max} set to 580 secs. This ensured that all nodes generated at least one event during the simulation time. The total number of events generated during the simulation was roughly equal to the number of successfully booted nodes. Address release was again controlled by a random timer. A node on receiving an address held it for a period of time between [R_{min}, R_{max}] before it sent a release packet to the sink. In our simulations R_{min} was set to 1 sec and the R_{max} was set to 200 secs. Making use of random seeds multiple simulation runs were completed for each network deployment.

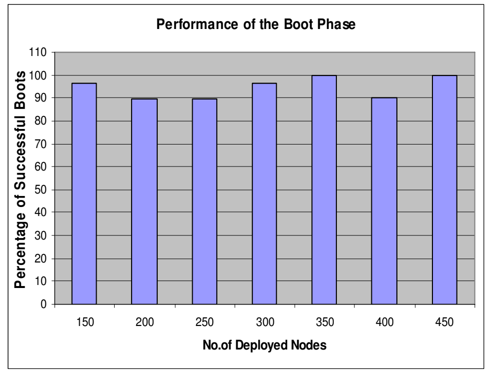

Figure 4 Performance of the boot phase

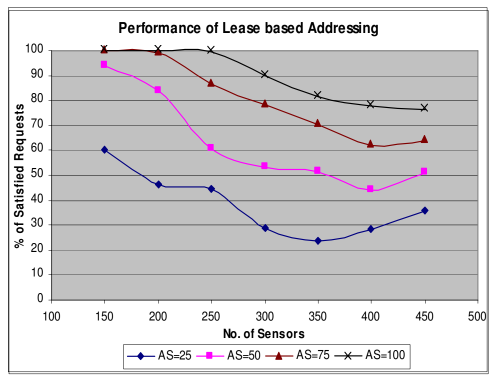

Figure 5 Percentage of Address Allocation

Figure 4 presents the percentage of successful nodes that were successfully booted during the boot phase of the addressing scheme. Only these nodes were allowed to generate events during the simulation time. It can be seen that in each deployment at least 90% of nodes were successful in receiving the boot packet and in negotiating a locally unique link-level address during the boot up phase (initial 30 secs). The failure of other nodes can be attributed to one of two factors - the failure to receive the boot up packet or delays in negotiating a link level address with their immediate neighbours. Figure 5 shows the performance of the addressing scheme with respect to successful reuse of addresses and the satisfaction of address requests. It highlights the main benefit of the lease based addressing mechanism. The different plots correspond to the four different address spaces that were used. It can be seen that a large proportion of address requests can be satisfied with an address size that is a fraction of the number of deployed (successfully booted) nodes.

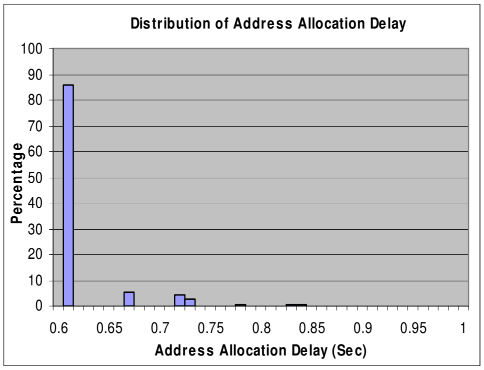

Figure 6 Address Allocation Delay

It can be seen that an address space of 50 addresses can satisfy almost 94% of all address requests in a random deployment of 150 nodes and around 84% in a deployment of 200 nodes. The 150 node deployment has a 97% boot phase success which roughly gives us a reusability factor of almost 3 in terms of address assignment. Such reuse will reduce the number of bits that need to be used for addressing and carried within each packet. In the 150 node deployment an address space of 75 gives us 100% satisfaction of all requests implying a reusability factor of 2. The 200, 250 node deployments have 100% satisfaction of address requests when the address space is 100 implying a reusability of 2 and 2.5 respectively (albeit with close to 90% success during the boot up phase). In the 450 node deployment we can see that only 76.49% of requests are satisfied with an address space of 100. In order for 100% satisfaction a reusability factor of 4.5 is required to be achieved. There exists a trade off between the size of the address space and the percentage of satisfaction.

Initial results relating to the delay experienced by a node as a result of the lease based addressing scheme was also calculated. Due to time constraints results were collected only for deployments of 100 nodes and less. It was observed that the delay introduced by the lease based mechanism is minimal. The average delay observed is around 600 msecs which we believe is quite acceptable. Figure 6 presents the delay distribution where almost 90% of address allocations are completed within 610 msecs.

6. Conclusions and Future Work

In this work we have presented a lease based addressing scheme for wireless sensor networks. The scheme is well suited for event driven wireless sensor networks and is able to achieve probabilistic reuse of addresses. We have presented both theoretical and simulation results for the scheme that prove it to offer significant benefits.

We hope to introduce additional mechanisms into the scheme such as rebinding of addresses and sink based timer to account for any lost release packets. Also we hope to study in detail the overheads and delays incurred due to the scheme.

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