AGRO-SENSE: PRECISION AGRICULTURE USING SENSOR-BASED WIRELESS MESH NETWORKS

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ABSTRACT

Advances in wireless personal area networks have made the practical deployment of various services possible, which until a few years ago was considered extremely costly or labor intensive. We build such a wireless sensor network for precision agriculture where real time data of the climatological and other environmental properties are sensed and relayed to a central repository. The architecture comprises of three distinct sections – (a) the sensor-nodes (b) the wireless mesh network and (c) the actuation components. The sensors are selected based on the properties suited for the most common crops and we identify four such attributes. The sensor network is based on the IEEE-802.15.4 standard and we develop a new static routing algorithm suited for the sensing application. The algorithm overrides the deficiency of the Hierarchical Routing scheme inherent in the ZigBee specification where the C_{skip} *addressing algorithm limits the possible depth of the network topology due to address wastage. The new algorithm maintains the hierarchical network topology and thus ensures routing at its optimal best. The algorithms for both addressing and routing are provided. The actuation components are also a part of mesh network and are activated wirelessly for controlling irrigation and fertigation.*

Keywords— IEEE 802.15.4, Wireless Mesh Networks, Routing Algorithm, Precision Agriculture

1. INTRODUCTION

Precision Farming is the conjunction of a new management perspective with the new and emerging information and communications technologies leading to higher yields and lower costs in the running of large scale commercial agricultural fields. Known also as Site-Specific Management, precision farming ensures quicker response times to adverse climatic conditions, better quality control of the produce and yet a lower labor cost. Precision Farming also makes the use of completely automated machinery, a possibility. This form of highly automated agriculture requires intensive sensing of climatic conditions at the ground level and rapid communication of the raw data to a central repository. At the central server, with the availability of computational power, decision making and control of farm equipment is done. The sensing technologies allow the identification of pests in the crops, drought or increased moisture. These can each have a devastating effect on the farm yield. Having such information at a real-time interval, automated actuation devices can be used to control irrigation, fertigation and pest control in order to offset the adverse conditions.

The Precision farming system has the following parts:

a) *Sensing agricultural parameters*
b) *Identification of sensing location and data gathering*
c) *Transferring data from crop field to control station for decision making*
d) *Actuation and Control decision based on sensed data*

Agricultural Sensors, positioning systems for detecting location of sensors, actuators like sprinklers, foggers, valve-controlled irrigation system, etc. are already available in market. However, very limited work has been done so far on the technologies to be used to transfer sensor data wirelessly from crop field to the remote server.

2. RELATED WORK

The concept of precision agriculture has been around for some time now. Blackmore et al., in 1994 [1] defined it as a comprehensive system designed to optimize agricultural production by carefully tailoring soil and crop management to correspond to the unique condition found in each field while maintaining environmental quality. The early adopters during that time found precision agriculture to be unprofitable and the instances of implementation of precision agriculture were few and far between. Further, the high initial investment in the form of electronic equipment for sensing and communication meant that only large farms could afford it. The technologies proposed at this point comprised of three aspects: (a) Remote Sensing (RS), (b) Geosynchronous Positioning System (GPS) and (c) Geographical Information System (GIS). The most important step in precision agriculture is the generation of maps of the soil with its characteristics. These included grid soil sampling, yield monitoring and crop scouting. RS coupled with GPS coordinates produced accurate maps and models of the agricultural fields. The sampling was typically through electronic sensors such as soil probes and remote optical scanners from satellites. The collection of such data in the form of electronic computer databases gave birth to the GIS. Statistical analyses were then conducted on the data and the variability of agricultural land with respect to its properties was charted. The technology apart from being non real-time, involved the use of expensive technologies like satellite sensing and was labor intensive where the maps charting the agricultural fields were mostly manually done. Over the last few years, the advancement in sensing and communication technologies has significantly brought down the cost of deployment and running of a feasible precision agriculture framework. Emerging wireless technologies with low power needs and low data rate capabilities, which perfectly suites precision agriculture, have been developed [2]. The sensing and communication can now be done on a real-time basis leading to better response times. The wireless sensors are cheap enough for wide spread deployment in the form of a mesh network and offers robust communication through redundant propagation paths [3]. Wireless sensor networks allow faster deployment and installation of various types of sensors because many of these networks provide self-organizing, self-configuring, self-diagnosing and self-healing capabilities to the sensor nodes. The applications using wireless sensor technology for precision agriculture are briefly explored below.

2.1. ‘Smart Fields’ Monitored by Wireless Nano-sensors and the USA’s Plans for a ‘Smart Field System’ [4]

“Since many of the conditions that a farmer may want to monitor (e.g., the presence of plant viruses or the level of soil nutrients) operate at the nano-scale, and because surfaces can be altered at the nano-scale to bind selectively with particular biological proteins, sensors with nano-scale sensitivity will be particularly important in realizing the vision of smart fields. The US Department of Agriculture (USDA) is working to promote and develop a total “Smart Field System” that automatically detects, locates, reports and applies water, fertilisers and pesticides - going beyond sensing to automatic application.”

2.2. SoilNet - A Zigbee based soil moisture sensor network [5]

“Soil moisture plays a key role in partitioning water and energy fluxes, in providing moisture to the atmosphere for precipitation, and controlling the pattern of groundwater recharge. Large-scale soil moisture variability is driven by space-time precipitation and radiation pattern. At local scales, land cover, soil conditions, and topography act to redistribute soil moisture. Despite the importance of soil moisture it is not yet measured in an operational way.”

“This project aims to develop a soil moisture sensor network for monitoring soil water content changes at high spatial and temporal scale. Main features of SoilNet are:

- ZigBee based Wireless Sensor Network with Mesh topology
- Very low energy consumption for long battery life
- Dynamic, expandable network (up to more than thousands of nodes)
- Able to react on external influences (change measurement frequency)
- Different node configurations for adapted measurement setups
- Measured data stored in a database (easy and variable access)

The small catchment area of the Wüstebach (about 26.7 ha) was proposed to be instrumented with the proposed soil moisture network SoilNet. The sensor network consists of 286 sub nodes and 12 coordinator nodes. The whole network was proposed to be managed by a main server that will also be connected with telecommunication (e.g. DSL) in order to enable online transmission to the workplace.”

3. PROPOSED TEST-BED FRAMEWORK FOR PRECISION AGRICULTURE

In this paper, we have designed a Wireless Sensor Network test bed for remote monitoring of agricultural parameters and accordingly controlling the irrigation and fertigation leading to Precision Agriculture. In our proposed system, Wireless Sensor Network is realized using IEEE 802.15.4 based LR-WPAN technology [6]. The architecture can be broken into three broad areas:

1. Sensing of agricultural parameters
2. Addressing of sensors and routing
3. Actuation and control decision based on sensed data

3.1. Description and design of Concept System

The wireless mess network comprises of the sensors placed at different locations in a crop field where the intended characteristics of the soil or atmosphere needs to be captured. The sensors’ analogue output is fed into a microprocessor based RF unit like the Chipcon CC2420 [7]. The data, now in digital form is packetised and dispatched to the central repository. The path taken by packets is determined by a new static routing algorithm (explained below). The route based on the location of the sensor vis-à-vis the central server typically comprises of multi-hops. Since the sensors with RF modules are static and each of them has a unique identity, an apriori association of sensors and its address can be made. The architecture is pictorially shown in figure 1.

The RF devices can be thought of as active RFID nodes. Each such node transmits its own identity and its location in the form of beacons. Every sensor also has its own identity as per its location and this information is apriori decided. The RF nodes are required to perform three roles as provided below. We may thus appropriately design the capability of the devices.

- Active RFID Gateway
- Active RFID tags with Sensors/Actuators
- Active RFID Routers

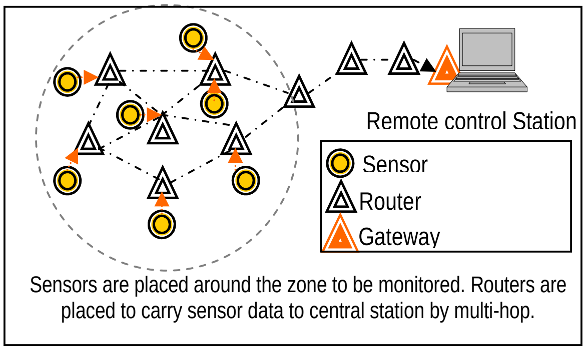


Figure 1. The sensor Network Architecture

3.1.1 Active RFID Gateway: Active RFID Gateway is essentially the master controller that coordinates the formation of mesh network, collects the tag data and transfers it to the host computer. It can also call as Coordinator. Having a specific role for an RFID coordinator, where we design and designate a particular device with the functionalities helps us provide an abstraction of the inner technology of the mesh network from the outside world. We may also convey the collected data over a GSM/CDMA mobile connection and essentially realize an “Internet of Things” paradigm.

3.1.2 Active RFID tags with Sensor/Actuators: Active RFID tag is connected with sensors can be used as a sensing device to sense different agro parameters and also regulates the actuators as per control decisions.

3.1.3 Active RFID routers: Active RFID routers can be used for range extension of active RFID devices. Routers are fixed at strategic locations within the tracking zones forming a IEEE 802.15.4-compliant wireless mesh network with other routers, gateway and active tags in its vicinity and the location of tags are determined in terms of the locations of fixed routers.

3.2. Sensing of agricultural parameters

Precision Agriculture entails the monitoring of various parameters which depend on the type of the crop being harvested. In our set-up, we have identified four parameters which are critical for most types of crops. The parameters are:

- *Soil pH*
- *Soil Moisture*
- *Electrical conductivity*
- *Soil temperature*

3.3 Addressing of Sensor/Actuator Nodes and Routing

The natural choice for the mesh network would be the ZigBee standard; however, the C_{Skip} algorithm used in ZigBee was found lacking when a sparse, but large network is needed. In this section, we first develop the need for tree based network and highlight its properties. We then move on to elicit the deficiencies of the current addressing algorithm in ZigBee. We thus propose a static addressing scheme where the routing is still maintained at its efficient best. This algorithm has been tested by way of an implementation for practical use on TI based boards – CC2420 [7].

3.3.1 Need for a tree based network topology

The ZigBee standard based on the IEEE 802.15.4 PHY and MAC Layers provides specifications for two kinds of network topologies- mesh and tree. Mesh networks utilize the slightly modified ad-hoc on-demand distance vector (AODV) [8]. However, we are interested and this paper delves on the hierarchical or the tree based routing scheme. As said above, the hierarchical scheme is preferred over a mesh networks in the realm of sensing and tracking applications. The characteristics of such applications are:

- A pre-determined area of deployment where the path to be sensed/tracked is known. Thus the routers (also known as Full Functional Devices - FFDs) are placed along this path.
- The data flow is always between the coordinator and an end device (also known as Reduced Functional Device - RFD) and vice-versa. There is never a need for two end devices to talk to each other.

The availability of apriori information of the location of the sensors and the coordinator dovetails with the hierarchical tree topology. By design, the location of routers can be optimized. This ensures low cost of hardware. The knowledge of the topology also provides the capability of theoretically determining the fault tolerance capability and establishes the bounds on latency. We can also study the bounds on network lifetime. Such bounds cannot be obtained from a mesh topology (since the topology is random and cannot be predicted). We thus favor the tree topology for planned deployments of sensor networks.

3.3.2 Deficiencies of the C_{skip} Routing Algorithm

The tree based routing has been shown to be the most efficient [9] among the different routing algorithms supported by ZigBee. However, this is conditional to the successful formation of the network topology in the form of a tree. ZigBee uses the C_{skip} algorithm for the address allocation and the buildup of the network topology. According to the C_{skip} algorithm, new devices which request association are given a short address. The address assigned follows rules set by the network parameters. These parameters are predetermined and are static. The

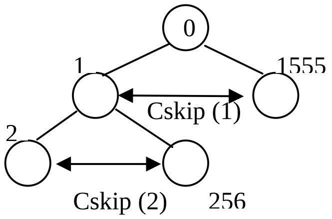
Parameters are C_m, R_m and L_m; where C_m= Maximum Number of children that a full functional device (FFD) can have; R_m = Maximum number or children (out of C_m) which are FFDs; and L_m = Maximum depth of the network. The values of these parameters are stored in the NIB (Network Information Base) in each device [10]. A device given to a requesting child is generated by the equation:

$$A_n = A_{parent} + C_{skip}(d) * R_n + n \qquad (1)$$

Where A_n is the address which the new device will take. A_{parent} is address of the parent of the device that will assign the address. $C_{skip}(d)$ is determined as follows:

$$C_{skip}(d) = \frac{\left(1 + C_m - R_m - C_m * R_m^{(C_m - d - 1)}\right)}{(1 - R_m)} \qquad (2)$$

$C_{skip}(d)$ determines the block of addresses which the parent device must skip before assigning the next address. The algorithm assumes the worst case scenario and makes provision for accommodation for all devices in the pre-determined network architecture. This assumption of a worst case scenario severely restricts the network depth. For example, values of C_m = 6, R_m = 6 makes L_m=7 for a 16 bit short address. The addressing scheme based on C_{skip} develops a tree topology which makes possible the optimum routing. Routing in such networks is made by comparing the destination address with the C_{skip} allocation block. If the destination address is within the C_{skip} block of any of its children, the packet is forwarded to that child, else the packet is forwarded to its parent. It has been shown that such tree based routing provides the minimum latency [9]. The address wastage problem in C_{skip} is pictorially shown below.



A sample topology with Rm = Cm = 6. If no more devices join the leg with node "1", a total of 1551 (1553 -2) addresses are wasted.

Figure 2. The address wastage problem in Cskip

3.3.2 The Static Addressing Algorithm

The motivation for a new algorithm arises from the need to prevent the wastage of address space but at the same time maintain efficient routing through a tree based structure. A pictorial topology is first prepared with the routers placed at appropriate distances along the path. The maximum number of end devices each router would have to handle is estimated (E_n). The address of each router is then determined by the simple algorithm as shown in figure 3. The algorithm works on the depth first concept where the deepest router is assigned an address first and the algorithm "works up" the topology. The needs of tracking allow us to set the address in advance to preserve the tree structure.

```
function main ()
{
  assign PAN_Coordinator_address = 0;
  current_address = $E_n$ + 1;
  assign_address ( PAN_Coordinator );
}

function assign_address ( node )
{
  for ( all children of node from left to right )
    assign_address ( child_node );

  node_address = current_address;
  for ( all children of node )
  {
    parent_address( child_node ) = current_address;
    append into address list, child_node address;
  }
  current_address += $E_n$ + 1;
}
```

Figure 3. The addressing algorithm

Every Router maintains an address list, which has the addresses of its child routers. The routing is done based on this. The address allocation is pictorially depicted in figure 5. Assume, a network topology as shown and E_n = 6. The addressing algorithm is akin to the C_{skip} in the sense of addressing in the depth first approach. However, C_{skip} assumes the worst case and would earmark addresses for non-existent nodes. This leads to a huge amount of address wastage and this precisely is avoided in the static algorithm. The sensing application has a well defined path and this is known in advance. Thus, the need to maintain addresses for future nodes does not arise. Further, the address allocation can be suitably tweaked to include an address provision for future nodes as the need may be. This can be achieved, by including a larger value for E_n. The address of a node denotes the maximum address of all devices under it. A router assigns address to end devices as node_address – n, where $1 <= n <= E_n$. At any given point, the property of the node addresses is maintained and thus routing is achieved. For example, consider an end device joins the network at node 35. It is assigned an address of 34. The routing decisions would be at each node and checks under which child, can the destination address exist and forward accordingly. The algorithm is shown in figure 4 and the sample routing in figure 5. The static addressing allows for a generic use and supports mobility of the sensors.

The addressing and routing algorithms have been tested on CC2420, TI (Texas Instruments) based board. The network layer was written over TIMAC (TI supplied PHY and MAC layers).

```
address_list = { child router addresses };
if ( dest_address = child_end_device )
  next_hop = dest_address;
else
{
  next_hop = parent_address;
  for all address_list_entries
    if ( dest_address of packet <= address_list_entry )
    {
      next_hop = address_list_entry;
      break;
    }
  loop
}
send_packet(next_hop);
```

Figure 4. The Routing Algorithm

3.4. Control and Actuation

The actuation is done based on the readings supplied by the sensors. Upon exceeding a threshold, the system will generate automated alert messages on the console, upon which appropriate action can be taken. Automated control can be incorporated into irrigation and fertigation systems.

Currently automated systems are available in drip irrigation and foggers. These valve based actuators will be controlled through special electrical switches at the controller end. The actuators (valves) will be operated according to the control decision. Each actuator will be attached to a RFID device to identify and control them uniquely.

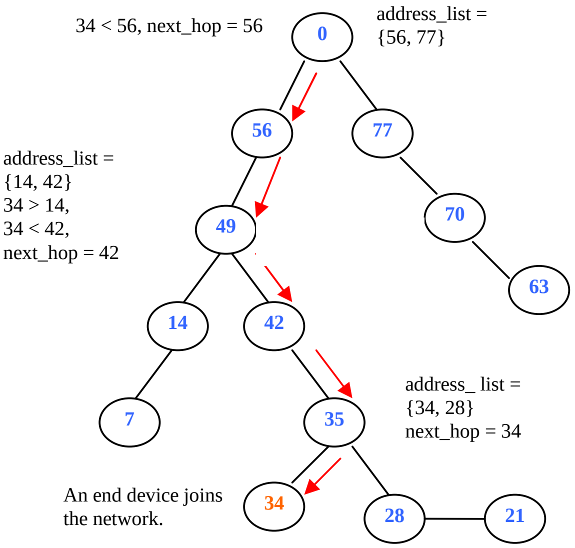


Figure 5. The path of a packet destined to “34” from “0”

4. CONCLUSION

In this paper we have developed architecture for Precision Agriculture based on wireless sensor networks. The architecture comprises of three distinct components: (a) Intelligent nodes with sensors/actuators (b) The wireless mesh network for communication and the design of a new routing algorithm and (c) The control and actuation. The sensor design is made based on the parameters to be sensed for the most common types of crops. We have enlisted four parameters, the soil pH, the Electrical conductivity, the soil temperature and the soil moisture. The mesh network is constructed in the form of a hierarchical tree, but we deviate from the ZigBee standard and build a custom network layer over the PHY and MAC of IEEE 802.15.4. The new routing algorithm is based on a static hierarchical architecture of the sensors where the need for mobility of the sensors is not high. In such networks, we can quickly build a network based on apriori information. In such scenarios, the address wastage inherent in the C_{skip} algorithm of ZigBee is avoided. Further, having a hierarchical topology ensures routing is maintained at its efficient best. The design of the control and actuation is made based on the available hardware in the market. The control decisions work on the sensed parameters through the rules housed in the central repository.

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