Towards a Multi-agent based demand-driven control of Building Systems.

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Abstract— **Occupant presence and behavior in buildings have been shown to have a significant impact on the energy consumed in buildings for space conditioning. Towards effort to improve the energy efficiency and performance of buildings, demand driven control of building systems and appliances have been proposed and implemented in a number of studies. A core component of demand-driven control in building operation is occupancy detection. The performance of the occupancy detection system impacts the controllability of demand driven applications, the accruable energy savings and comfort of building users. This paper provides initial results from an ongoing research into the development of a multi-agent system (MAS) coordinated demand–driven control application for building operations which utilizes a robust and low-energy wireless sensor network (WSN) technology for occupancy measurement.**

Keywords—Multi-agents; Wireless sensor networks; Energy; HVAC systems

I. Introduction

It is a well-established fact that the primary role of buildings and building services is the provision of a comfortable, healthy and safe work as well as living space for its inhabitants [1]. In performing its functions, buildings have been shown to account for between 30-35% of total final energy consumption in the USA, EU and other Organization for Economic Cooperation and Development (OCED) countries [2-4]. The impact of building energy consumption on the sustainability of non-renewable energy supply sources and greenhouse a gas emissions has resulted in it being the target of a number of energy efficiency improvement strategies [5]. To this end, buildings have been identified as a key potential contributor to efforts to safeguard security and sustainability of energy supplies as well as efforts to mitigate climate change [6].

In buildings, lighting, heating, ventilation and air–conditioning systems are the top energy consuming systems, both accounting for more than half of total energy consumed [7-8]. Several studies have shown that the interaction of building occupants with these building systems and their controls has a greater impact on energy consumption [9]. It has therefore become more important to understand individual behavior of building occupants as well as fine-grained evaluation of energy end point utilization in buildings in order to help reduce energy consumption and carbon emissions in existing buildings.

Demand-driven control strategies are measures aimed at improving the energy efficiency and performance of building systems through the use of actual building occupancy information. This includes measures such as turning off or dimming artificial lighting systems and controlling the ventilation, heating and cooling of spaces using actual occupancy information. As demonstrated in a number of studies [10], energy savings of between 3-84% can be achieved in office buildings through demand driven control of lighting systems. Also as demonstrated by the authors in [11] through dynamic occupant driven use and control of HVAC systems in an office, energy savings of up to 30% was shown to be attainable. A core component of demand-driven control applications in building operation is occupancy information. Information on occupancy, may lead to very fine delivery of lighting and heating, ventilation and air conditioning and visualization of the use of space.

Over the years, a number of studies [12] have developed occupancy prediction models for control processes in building operation. Though with impressive results, these models are often building specific and do not proffer a generic solution to occupancy measurement in buildings, which varies with a building's functions, location and person. As a result, most commercial buildings still operate based on fixed schedules and assumed occupancy information, despite studies showing that average occupancy in buildings even at peak times is usually below 70% [13-14].

Of recent however, non-model based generic solutions providing near real-time occupancy information and based on wireless sensor network technologies [15-16] are been considered in demand-driven control applications in buildings.

In addition, for coordination of demand-driven control applications, solutions based on the multi-agents design paradigm are also been introduced in building operation as a result of their distributed, autonomous and adaptive capabilities [13, 17].

The subsequent sections of this paper describe the design framework for a MAS coordinated demand driven control of building systems and appliances utilizing wireless sensor networks for occupancy detection. The proposed system can be integrated into existing building's comfort and energy management system for control of lighting & HVAC systems to improve buildings responsiveness to demand response and smart grid interaction. Initial experimental results from the test-bed building are also presented as well as the energy savings obtainable from the application of the proposed system in operation of the building.

II. BACKGROUNG

A. *Sensor network and localization*

The advancement in radio and embedded systems technology has significantly enhanced the proliferation of various wireless communication systems in a large number of end-use applications. A representative of this class that has received considerable attention from the research community is wireless sensor network, which consist of numerous tetherless devices that are released into the environment and organize themselves in an adhoc fashion [18, 19]. The main goal of wireless sensor networks in most application is to perform monitoring tasks and a key component of tasks monitoring applications is information on the location of occurrences/events. Not only is this information needed for the sensor network to report the location where events take place, it also assists in group-querying or routing traffic to a designated geographic destination and provides information on physical network coverage [18].

In general they are composed of three major components as depicted in figure 1[15, 18]; (a). A transmitting device- with the capability to communicate with other nodes within a certain communication range using signals such as radio frequency (RF), acoustic, infrared and ultrasound [19,20]. The nodes can either be an active or passive and includes devices such as RFID (radio frequency identification) tags, mobile phones, laptop computers enabled with a transmitter; (b). A receiving device or readers; (c). A data collection and processing sub system.

In applications requiring localization, the system measures either the timing or energy of the transmitted signal and uses the information to estimate the location of mobile nodes. A detailed discussion of these methods can be found in [19]. In wireless sensor network applications based on RF signals, the received signal strength indicator (RSSI) which is used for network planning and localization [18]. Measurement of the RSSI from nodes is a distance estimation technique that uses the measured signal power at the receiver and the known transmit power to estimate propagation loss. The propagation lose is subsequently translated into distance using theoretical models.

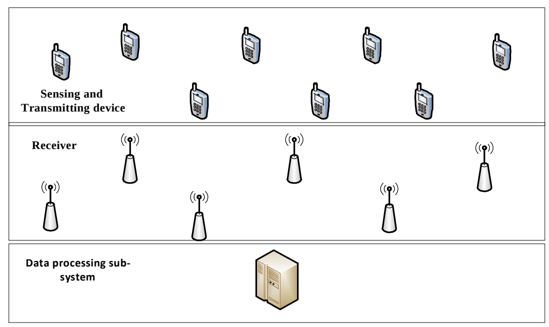

Figure 1: Client/server Wireless network components

B. *WSN in Demand driven applications in buildings*

For demand driven control applications in buildings, the common desires information on building occupancy as shown in figure 2 includes [16, 21];

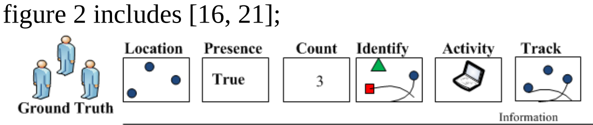

Figure 1: Occupancy Information

(A).Location- which provides information about 'where' in the building or particular thermal zone within the building occupants are situated (B).Presence- provides information about 'when' particular occupants are in particular thermal zones within a building; (C).Count- provides information on the 'number' of occupants in a particular thermal zone; (D).Identity-provides information on 'who' is in particular thermal zones; (E). Activity- provides information on 'what' activity is been carried out by individual occupants in particular thermal zones. (User activity determines the body metabolism rate which is one of the parameters required in the determination of thermal comfort [22]); (F) Track- provides information about particular occupants movement across different thermal zones in the building.

In a comparative study, the authors in [20] investigated the performance of different wireless systems utilizing the RSSI distance estimation method in indoor localization applications. Also using RFID tags, the authors in [15] demonstrated the capability a system utilizing the RSSI distance estimation technique to provide information on location, presence, count, activity, identity and track. In both studies and other similar studies on the use of WSN in building operations for localization [23-25], the network design were mostly centralized and based on the client/server communication architecture depicted in figure 1. In client/server network architecture, static nodes with known locations transmit messages such as; the received signal strength indicator, contact time, and nearest neighbor information to a processing station wherein, the position estimation algorithm is installed.

In occupancy measurement for demand driven control applications in buildings, the centralized nature of the client/server localization architecture does however pose a number of challenges:

(a) **Delayed control response time**- Users might have to tolerate some level of discomfort as a result of the delay from aggregated communication between the sensing, control and actuation nodes [26].

(b) **Complex and high computing requirement-** In studies that have demonstrated the feasibility of wireless sensor based localization [15, 20] indoors, a limited number of participants were considered and complex computing was required to obtain the needed information. In a typical commercial office building, occupancy count is usually much higher than demonstrated in these studies, thus becoming more complex and requiring more processing power.

C. *Multi-agent systems(MAS) for demand driven control applications.*

Considering the drawbacks of the client/server WSN architecture in demand-driven control applications in buildings, solutions based on the MAS paradigm have been proposed [13, 26]. In artificial intelligence, agents are physical or virtual entities that intelligently interact in an environment by both perceiving and affecting it [13]. Consequently an agent can be described as a computational system with a high degree of autonomy performing actions based on the information received from the environment. A system comprising multiple intelligent agents, commonly referred to as a multi-agent system (MAS). Within a MAS, agents interact to achieve cooperative (e.g. distributed problem-solving) or competitive (e.g. coalition formation, auction) group behavior. Agents achieve this by sharing a minimum amount of information between modules and asynchronous operation implemented via message exchanges [27].

The concept of intelligent agent technology is at an intriguing stage in its development as commercial strength agent applications are increasingly being developed in domains as diverse as manufacturing, Unmanned Aerial Vehicle (UAV) mission management and in operation and management of the smart grid [27-28]. In wireless sensor network applications, they are capable of roaming in the network, collecting data, aggregating and making decisions at the node level [29]. The agent paradigm promotes the use of independent, loosely coupled software entities that encapsulate some specific functionality and interaction with each other to solve tasks. The authors in [27-31] summarize the key features of MAS as:

- **Autonomous nature**- agents can act rationally and operate without the direct intervention of humans. They have individual internal states and goals, and act in such a manner as to meet their goals. A key element of autonomy is pro-activeness, i.e., the ability to ‘take the initiative’ rather than acting simply in response to their environment.
- **Co-operation**- agents may interact with each other both indirectly (by acting on the environment) or directly (via communication and negotiation). To co-operate, agents need to possess a social ability, i.e., the ability to interact with other agents and possibly humans via some communication language.
- **Intrinsic distributed nature**- A MAS system is a distributed system consisting of multiple agents, which forms a loosely coupled network, in which agents work together to solve problems that are beyond their individual capabilities or knowledge of each individual agent. In addition, they are mobile, scalable and modular, able to transport from one machine to another
- **Learning ability** - agents are able to learn and adapt to changes in the environment they live in. A key attribute of any intelligent being is its ability to learn and for agent systems to be truly intelligent, they would have to learn as they interact with their environment. In addition, agents are reactive which makes them respond to changes in the environment in a learned way and timely fashion. Agents are also goal oriented, acting in own self-interest and do not just act in response to the environment.

III. PROPOSED SYSTEM ARCHTECTURE .

A. *General System Architecture*

Leveraging on the above described capabilities of MAS, we propose a system with the architecture depicted in figure 2 and comprised of the following agents- manager, room, zone, building, and occupancy and user agents.

Manager agent- MAS design paradigms provides a flexible framework in which agents can be included and remove at any time without causing disruption in the systems operation. It is however necessary to have up-to-date information about the state of agents operating in the system. The task of the Manager agent is thus to monitor all agents (active, passive, dead or alive) operating in the system.

Room-agent- The room-level is critical for striking a balance between user comfort and energy efficiency as this is where both goals have contradictory requirements. The role of the room agent is hence a decision maker. Using information on the room properties, actuation and control possibilities, room state, occupancy information as well as user preference, the room agent determines the optimal room condition to satisfy the building policy on energy and comfort.

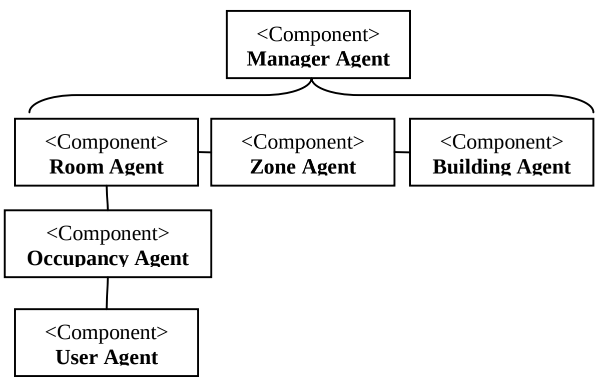

Figure 2: Architecture of the proposed MAS Demand control system

Zone-agent- In the design of building thermal systems, it is common to have areas of a building having similar cooling/heating requirement to be either virtually or physically grouped. A zone can thus be a group of rooms, a single room or multiple floors, which share comfort resources such as ventilation, heating and cooling. Depending on the building layout and design, the zone agent is responsible for optimal delivery of required comfort index of occupants located within particular zones in an energy efficient manner. In cases where the distribution of resource is shared with multiple rooms, the room agent would have to communicate with the room agent on the most efficient means of resource sharing.

Building agent- The building agent performs the role of an aggregator. It collates and aggregates information on energy utilization within the building. With more fine-grained information on energy utilization in the building, the buildings responsiveness to demand response and smart grid interactions can be improved [32].

Occupancy Agent- The occupancy agent provides the room agent with more fine-grained occupancy information. Further detail on the occupancy agent is provided in subsequent sections.

User Agent- The user in conjunction with the occupancy agent provides information on user identity, preference and activity to the room agent.

B. Physical Architecture.

The physical architecture for the proposed MAS system for an Integrated Room Automation (IRA) for office buildings is depicted in figure 3. IRA deals with the automated control of blinds, electric lighting, heating, cooling, and ventilation of an individual building zone or room. As shown, the setup is comprised of three agents- the user, room-occupancy, and room agents.

Users-agent- The user agent are mobile devices such as RFID tags, mobile phones or devices with radio signal transmission capability. Each building user is provided with a device which is unique to individual building occupants. This agent provides the room-occupancy agent with user identity information (tag ID), activity (analysis of the RSSI) and presence.

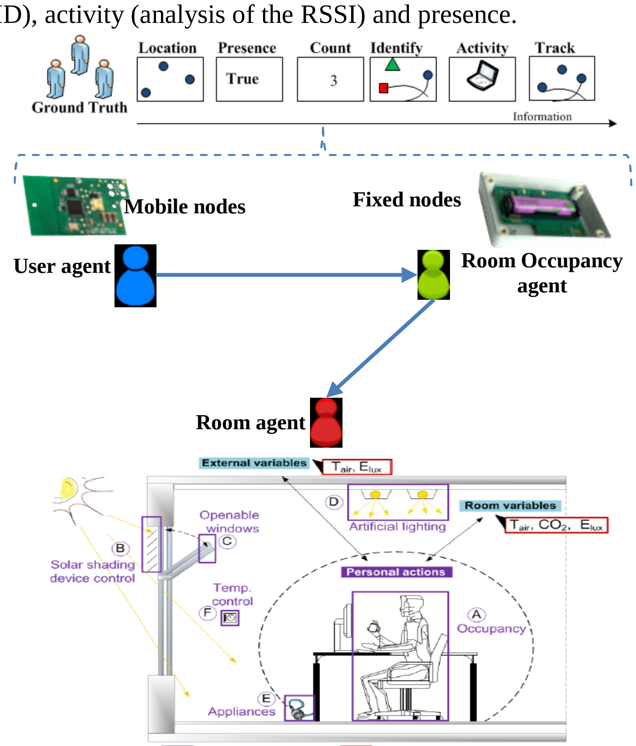

Figure 3: Physical architecture of the proposed System.

Room-occupancy agent- These are fixed nodes with assigned to particular building rooms and other known locations such as exits, conference rooms and lunch rooms. The room-occupancy agent obtains the RSSI from mobile nodes as well as the ID. It analyses the RSSI signal and provides information about user presence, count and activity which is sent to the room agent. For tracking, room occupancy agents at known locations exchange information with room occupancy agents assigned to particular rooms. As an example, through measurement of the RSSI, the room occupancy agent assigned to room A of an office building is able to determine if the particular room occupant through the tag ID has exited the room to the conference room. It however awaits information from the room occupancy agent in the conference room before passing the information to the room agent.

The room–agent- The room agent receives occupancy information from the room occupancy agent assigned to individual rooms and adjusts the room conditions based on the received information. As an example, since each building occupant is attached to known offices and do have a unique ID. When the room agent receives information about the presence and departure of unassigned user ID's in the room it is assigned, it sends the needed control signal to the room actuator so as to conserve energy and improve user comfort.

In addition, considering the slow response of some building systems such as HVAC systems, the room agent uses the track information provided by the room-occupancy agent to make time-dependent adjustment to building systems in a manner that does not disrupt the comfort of building occupants.

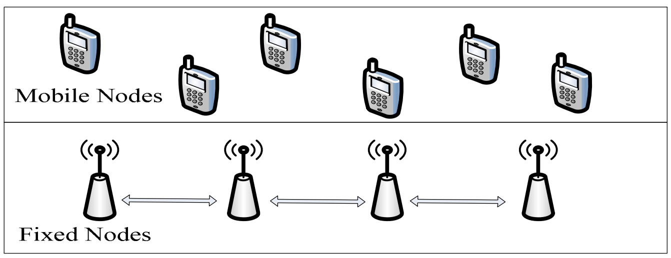

Figure 4: Agent based detection system

In contrast to the typical client/server wireless network model, the required information such as user location, presence and identity is shared between nodes. As information exchange is between nodes and decision making is decentralized, network resource is more adequately utilized thus reducing congestion while also making the systems more robust.

IV. EXPERIMENTAL SET-UP

A. *The wireless network*

In order to test the performance of the wireless sensor network indoors as well as to provide data for performance comparison, a WSN for occupancy detection was implemented in a test-bed office building. Utilizing a low-cost, low power WSN system based on the MyriaModem and MyriaNed [33]. For communication between nodes, the network does not utilize any particular topology but utilizes a gossip mechanism. To accomplish synchronization between wireless nodes without the risk of a separate network evolving, a join mechanism is embedded in the nodes. Through this mechanism all nodes are synchronized.

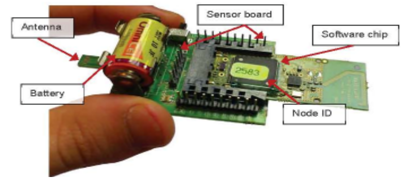

Figure 5: Mobile and static nodes

B. *Test-bed office building.*

The initial test setup was implemented on the whole floor of an office building with area of approximately 500 m^2. The floor is made up of 29 flexible open plan work spaces and 5 cell offices. For the purpose of this experiment, 18 employees with workspaces located in the flexible open plan spaces participated fully for a period of three weeks.

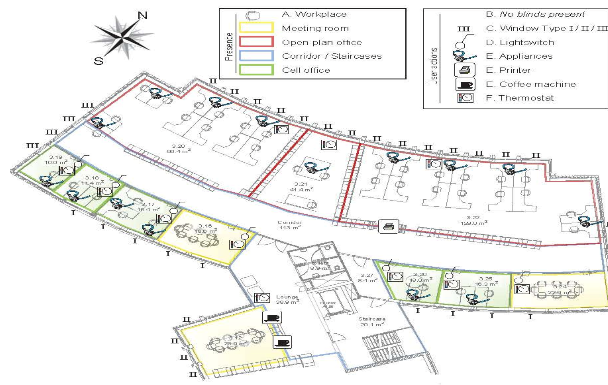

Figure 6: Test-bed office building

Each participant was assigned a node depicted in figure 4. The static and mobile nodes are physically the same but run different application software.

C. *Experimental Results*

Using the described client/server WSN localization architecture, static nodes were programmed with known locations and provided location estimation with their own known locations. Based on the signal strength from the surrounding static nodes, the mobile node takes over the location of the closest static node, which is sent along with the tag ID, time and location to the server.

Location information- Static nodes were placed at known locations such as users' workstations, coffee as well as printer locations. Post –processing of the obtained data as depicted in figures 7 & 8, shows that participants were only at their workspace for less than 70% through the duration of the study. For about 30% of the time spent within the office building, participants were at other locations. An interesting discovery however, was the fact that even at these periods when occupants were at other locations, the energy consumption of building appliances and systems as depicted in figure 8 remained unchanged.

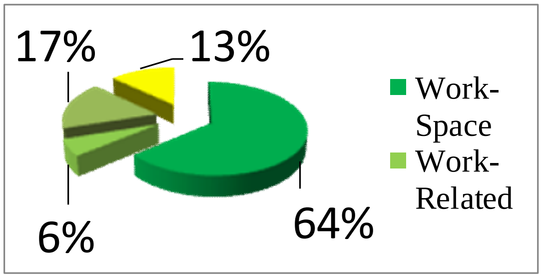

Figure 7: Occupancy Distribution

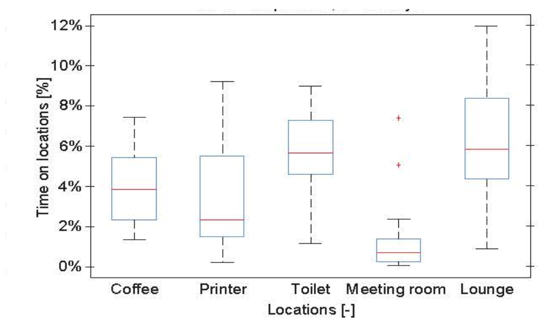

Figure 8: Percentage of time participants were present at other locations

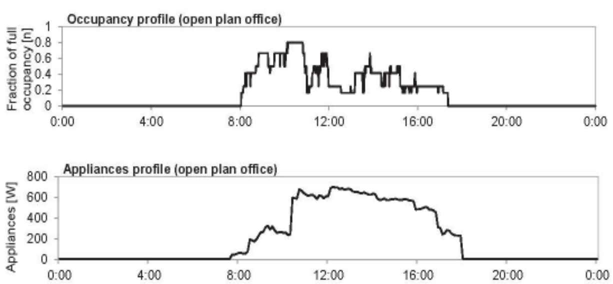

Figure 9: occupancy and appliance energy use

Presence information- Each of the participant had a mobile node on their person thus making it relatively straight forward to determine their presence at each location**.** Post processing results did however show that the average presence was below 60% for this particular office building for the duration of the study. Other similar studies have also shown that average presence in buildings is using less than 70% even at periods of peak occupancy [13, 14, 34].

Count Information- Since each occupant was with a tag, establishing the number of participants was also a relative easy task. It was however observed that participants did at some point forgot to make use of their tags.

Identity- Each participant was assigned particular nodes, which also had unique ID's used to distinguish different participants.

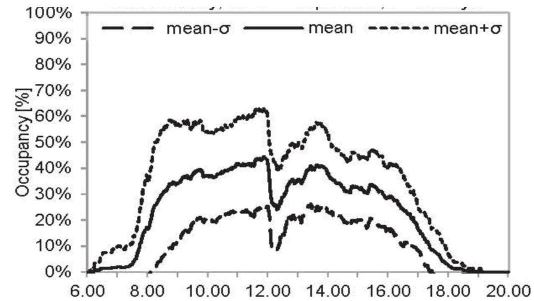

Figure 10: Mean Occupancy.

Track- participants locations as depicted in figure 8 was obtained through post-processing of the data sent to the server from the receiver nodes.

V. Discussion

As shown through the implementation of the client/server localization architecture, obtaining information on track, activity as well as location would require so more network resource if it is to be used for demand-driven control applications in building operations in particular for control of HVAC systems. Utilizing the distributed and autonomous properties of MAS as well as the described MAS based architecture does however reduce the overhead. Since nodes have more autonomy and can exchange information with other nodes, obtaining tracking and presence information utilizes minimal network resources thus making the WSN more robust.

VI. Conclusion and Future work.

In this paper, the framework for a multi-agents coordinated occupancy detection system for demand-driven control applications in building to improve buildings energy efficiency as well as responsiveness to the smart grid was presented. The framework described uses a different approach from the conventional client/server network architecture commonly for localization in wireless sensor networks. Initial experimental result from a test-setup in an office building using the typical client/server WSN architecture was presented. The proposed MAS based system is currently under development and would be implemented in the test-bed office building. Its performance would be evaluated with results obtained from the client/server WSN model.

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