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Power Cluster: an Efficient Clustering MAC Protocol for RF Rechargeable Wireless Sensor Networks

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ABSTRACT

Recharging a sensor node by using energy harvesting techniques is increasingly gaining importance in recent trends. One popular method of energy harvesting is the use of RF waves to increase the battery lifetime of the sensor node. The use of dedicated RF energy for energy harvesting requires commercial off the shelf products making the cost of the network feasible. However, the energy transfer occurs in the data communication band thereby requiring an efficient protocol to share the medium appropriately. We propose a clustered approach to solve the issue of compromise between energy and data transfer. By extensive simulations, we show that the proposed protocol optimizes the energy harvested by each sensor node while causing minimum interruption to data communication.

INTRODUCTION

Wireless sensor networks (WSNs) are used for a multitude of applications in day to day life. Remote patient monitoring, habitat monitoring, smart homes, structural health monitoring etc are hot scenarios where WSN are intensively used. Off late many developments in the field of sensor nodes have resulted in emerging applications with low cost and low maintenance WSN. Still the main chokepoint in WSN is the restricted network lifetime due to the battery constraints of the sensor node. Since the nodes are deployed usually in a hostile environment it is not only impractical but also infeasible to manually replace the battery of the sensor nodes. One practical solution is to use rechargeable batteries in the sensor nodes that can be charged by other external means. Several approaches have been described in (Eu, Z.A., 2011), to recharge the battery by use of solar, wind, acoustic, vibration etc. The out of band energy transfer proposed in (Kim, J., J.W. Lee, 2011), as well as the above mentioned ambient sources result in additional hardware and also requires excess spectrum availability and thereby increasing network cost. The proposed scheme uses in-band energy transfer and needs only an additional circuit to harvest energy from RF power sources. However, use of in-band approach causes the MAC protocol should tackle the challenges like scheduling the energy transfer, precedence of energy transfer and its influence on communication services. The MAC protocol must consider nodes requesting channel for data transfer and nodes requesting RF power for recharging with fairness and provide mechanisms to tackle collision between the two. In our protocol, the WSN consists of a set of dominator nodes which by harvest energy from other ambient sources such as solar, vibration, wind and biochemical but not by RF energy. These dominator nodes act as a source of power to the sensor nodes by providing them RF power. Each dominator forms a cluster of sensor nodes during the initial start-up phase of the network to which it supplies RF power for recharging the node. In our approach there is no need for global synchronization but we need only cluster synchronization. When the energy of the sensor node becomes lesser than the predefined threshold then the node asks for RF

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power to its cluster dominator using PowerRequest (PR) signal. The nodes in the vicinity of the requesting node also go into recharging mode when the dominator provides RF energy.
The main contributions of our work are as follows

- A novel approach for clustering of nodes for RF power transfer.
- A time schedule is identified to separate RF power transfer and data transfer
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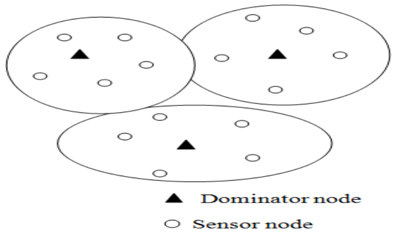

Fig. 1: Network Architecture.

The rest of the paper is organized as follows. Section 2 briefs the related work is provided. In Section 3, the set up model of the Wireless sensor network considered is described. Section 4 provides the overview of the proposed protocol. Section 5 explains the MAC framework in detail followed by performance analysis in Section 6. Section 7 concludes our work.

II. Related Work:

In (Naderi, M.Y., 2014), the authors proposed a distributed MAC protocol for RF energy harvesting sensors using in-band energy and data transfer. However, the protocol does not solve the issue of idle listening and provides energy access priority over data causing critical data communication to be disrupted. In the authors proposed a centralized MAC protocol for WSN with RF energy harvesting. In this approach the node adopts a duty cycle based on the energy harvested by it. This protocol requires global synchronization and uses out of band energy transfer. In (Watfa, M.K., 2011), authors present concept for multi hop wireless energy transfer and derive the efficiency of the same. This method however has a disadvantage that it requires magnetic coupled resonators with perfectly aligned coils among the transmitter and receiver. In (Chen, L., 2014), a token MAC protocol system is detailed which provides fair access to the medium for all tags but this system is not capable to generate enough energy for a typical sensor node. The authors in (Curty, J.P., 2006) presented RFID technology in which the RFID tag operates by using the energy from the RF Power incident on it from the transmitter. (Iannello, F., 2012) discussed the design of and analysis of MAC protocols of sensor networks which are recharged by using ambient energy harvesting.

III. Setup Model:

The network consists of dominator nodes and sensor nodes. The dominator nodes are assumed to have no power constraints and can easily charge up the sensor nodes in its power cluster. Sensor nodes in network are provided with the RF energy harvesting circuit and a super capacitor. The dominator nodes provide RF Power to the normal sensor nodes which in turn charges the super capacitor. The sensor node uses its residual energy for the operations like sensing, computing, packet transmission and reception, which is powered again the recharging mode.

IV. Overview of the Protocol:

The protocol consists of two phases, the initial start-up phase and the steady state phase.

4.1. Initial Start-up Phase:

The initial phase consists of power cluster formation and is identified by advertisement phase and setup phase.

4.1.1. Advertisement phase:

In this phase the dominators send a short pulse in the slot allotted to them. The sensor nodes listen to the pulse and select their cluster dominator as the one which has the highest RSSI. The node identifies its recharging duration to power up the super capacitor from the threshold to its maximum value. This is indicated back to the dominator.

4.1.2. Setup phase:

The dominator on receiving interest from the nodes to form a power cluster comes up with the schedule for the nodes to aid in transmission and reception. This schedule is published to the cluster nodes.

4.2. Steady state phase:

After the completion of initial start-up phase each dominator is aware of the set of nodes to which it should service energy. The node also identifies its cluster dominator and the amount of time required for it to completely recharge. The steady state phase consists of a set of periodically repeating cycle of active mode followed by a sleep mode. Each period consists of an active duration and sleep duration. The active duration follows slotted CSMA during which data transmission occurs. In the sleep duration, the sensor nodes switch their radio off. During the sleep mode, the node can request for RF power to its cluster dominator by sending a Power Request (PR) signal by indicating its charging period as computed in Section 5.1.1 .

V. Detailed Protocol Description:

The protocol operation can be explained by two phases; initial start-up phase and the steady state phase

5.1. Initial Start-Up Phase:

In the initial start-up phase, the power clusters are formed. Each dominator node identifies a group of nodes it grants Power Request's. The initial start-up phase comprises of Advertisement phase and setup phase

5.1.1. Advertisement Phase:

This phase is detailed by the following set of operations. Every dominator node is provided a time slot for it to send a beacon signal. All nodes listen to the beacon signals and identify the dominator with the highest RSSI (i.e., the dominator which is the nearest to them). The equation is computed from the energy of the capacitor as

$$E_{required} = \frac{1}{2}C(V_{required}^2 - V_{current}^2) \quad (1)$$

In our case $V_{current}$ ~ 2V and $V_{required}$ = 3.3 V which are the minimum and maximum operating voltage for Mica2 mote. Thus the value of $E_{required}$ is computed by

$$E_{required} = 2C \quad (2)$$

$$E_{required} = \frac{P_R T_{rd}}{T_{slot}} \quad (3)$$

where C is the capacitance of the capacitor , P_R is the power received in the beacon signal and T_{slot} is the duration of the beacon signal.

The recharging duration of the node is computed as

$$T_{rd} = \frac{2C}{P_R} T_{slot} \quad (4)$$

The dominator beacon which causes the minimum value of T_{rd} is chosen as the cluster dominator.

5.1.2. Setup Phase:

In the setup phase, the nodes indicate the interest of forming a power cluster to the chosen dominator node in the advertisement phase. The dominator node accepts the interest from the nodes. It estimates a cycle schedule for the cluster nodes. Every cycle consists of a beacon signal from the dominator followed by an active mode and a sleep mode. The beacon signal is of the duration 15 µs. The duration of active mode and sleep mode is decided by the cluster dominator node based on the number of cluster sensor nodes. The active duration T_{active} and the sleep duration T_{sleep} are computed similar to the IEEE 802.15.4 standards [8] by

$$T_{active} = 2^{N_k} \text{ x } 15.38 \text{ ms} \quad (5)$$

$$T_{sleep} = 2^{S_k} \text{ x } 15.38 \text{ ms} \quad (6)$$

where $0 \leq N_k \leq M$; $0 \leq S_k \leq N_k$

This schedule is published to the cluster members by the cluster dominator.

5.2. Steady State Phase:

Each cycle in the steady state phase comprises of a beacon signal from the dominator cluster followed by active and sleep mode. The cluster dominator node sends a beacon signal indicating the start of a cycle. There are three types of beacon signals viz., normal beacon, cluster power beacon and vicinity power beacon. In the active mode, if the node residual energy is than the predefined threshold (V_c ~ 2 V) , the node switches off its radio in the active mode and waits till the sleep mode. Else the nodes contend the channel access for packet

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transmission by slotted CSMA using the allotted code. The DIFS duration for the slotted CSMA is 320 µs similar to the IEEE 802.15.4 standards (Howitt, I., J. Gutierrez, 2003). When the node has no packet for transmission it waits for any other node to receive a packet in the active period. In the sleep mode, the node switches OFF its radio and waits for the start of the next active cycle. When the node requires RF power from the cluster dominator, it switches ON the radio during the sleep mode and sends a Power Request(PR). PR signal indicates the node ID and the recharging duration T_{rd}. The cluster dominator receives the PR and indicates the acceptance by sending a cluster power beacon indicating a RF Power cycle. The cluster power beacon contains information about the node ID which requested the RF Power transfer along with the duration of RF Power transfer and the time of the start of the RF Power transfer. Usually the RF Power transfer takes place in the sleep mode of the power cluster. If there are no PRs received by the cluster dominator, the dominator sends a normal beacon to signal the start of the next cycle. On sensing a power beacon, the neighbouring dominators transmit a vicinity power beacon signal which informs the nodes about the time of RF power transmission. The nodes in the vicinity of the dominator cluster enter into recharging mode on hearing a vicinity power beacon. The dominator cluster sends RF power after the commencement of the sleep mode. The sensor nodes in the cluster as well as those nodes in the vicinity of the cluster recharge using the RF power. After the end of recharging mode, the dominator cluster sends a normal beacon signal indicating the start of the next cycle. The flow of operations is illustrated in the Figure 2.

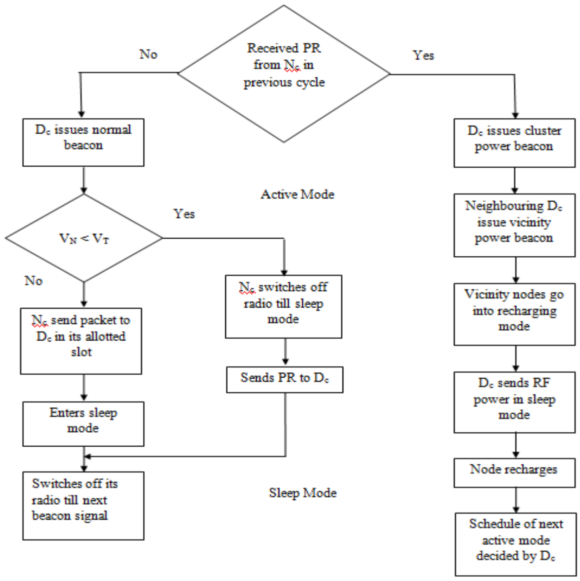

Fig. 2: Operations in Steady state phase.

VI. Performance Analysis:

In this section, we evaluate the performance of the protocol by simulation analysis. The protocol is compared with RF-MAC, where the ET's are treated as nodes for packet transfer in order to have a fair comparison along with a Clustered CSMA MAC protocol where the nodes form power clusters but do not have a cycle of active and sleep modes. The performance metrics are the average packet loss and the average number of PowerRequest's per node. The average packet loss is computed by estimating the averaging the number of packets dropped against the total number of packets during the simulation. The average number of PowerRequest's per node is found by recording the number of times a sensor node requests for RF Power and averaging the value during the simulation. The parameters of the simulation are set as follows. The energy harvesting circuit parameters are based on (Nintanavongsa, P., 2012). The operational characteristics of the sensor are modelled on Mica2 mote specifications. 200 sensor nodes are uniformly deployed at random in a grid of 400 x 400 m^2 area. The grid is subdivided into grids of 10 x 10 m^2 area in which 40 dominators are placed at the centre of each grid. The traffic load is generated by CBR flows. Sender receiver pairs are identified randomly.

6.1 Evaluating Dominator node density:

In Figure 3, the ratio of the dominator node with the sensor node is varied to find the appropriate dominator node density for this network. The packet loss ratio for 1:4 is almost similar to 1:5. However, 1:3 results in an increased value of packet loss. Hence we can fix 1:5 as the ideal ratio for the current scenario.

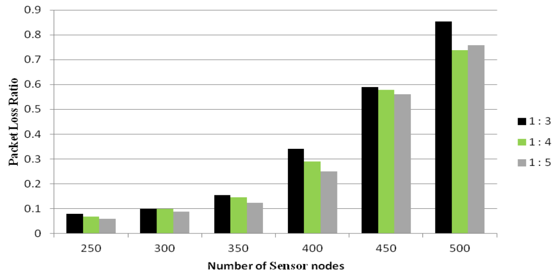

Fig. 3: Effect of Dominator node density.

6.2. Effect of number of flows:

The impact of increasing the number of data flows is investigated. Figure 4shows the average packet loss when the number of data flows is varied from 1 to 5. The average packet loss is significantly less in the proposed protocol when compared to and Clustered MAC. The nodes are clustered for energy transfer to a cluster dominator causes lesser amount of RF Power interference than RF-MAC.

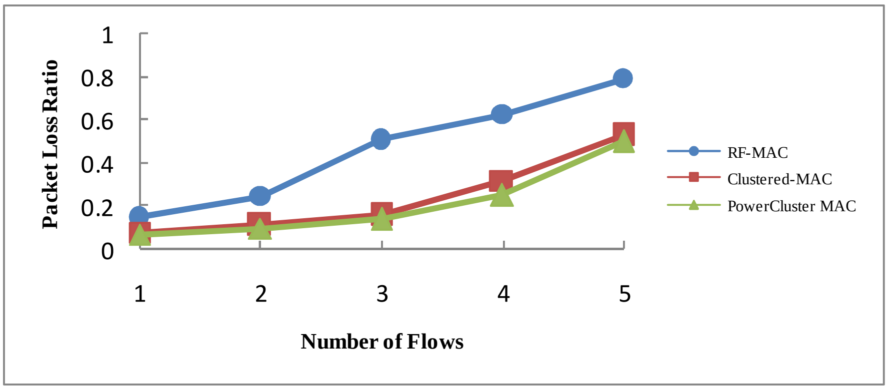

Fig. 4: Effect of Number of Flows on Packet Loss Ratio.

6.3. Impact of Node Density:

We investigate the network performance by varying the number of sensor nodes from 250 to 500. The dominator nodes are increased correspondingly in the ratio of 1:4 with respect to the sensor nodes. The variation of the average packet loss with the node density is shown in Figure 5. As the node density increases, the network becomes crowded resulting in a similar packet loss for all the three MAC protocols.

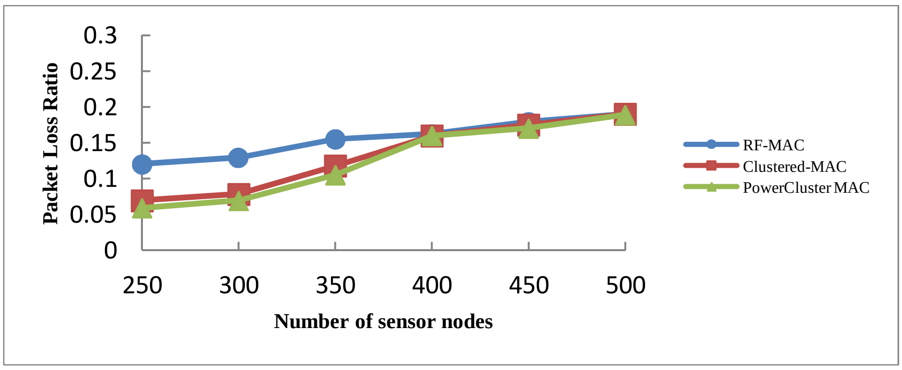

Fig. 5: Effect of Node density on Packet Loss Ratio.

The effect of node density on the number of Power Request's is shown in Figure 6. The average number of Power Request's shows a decrease as the node density increases.

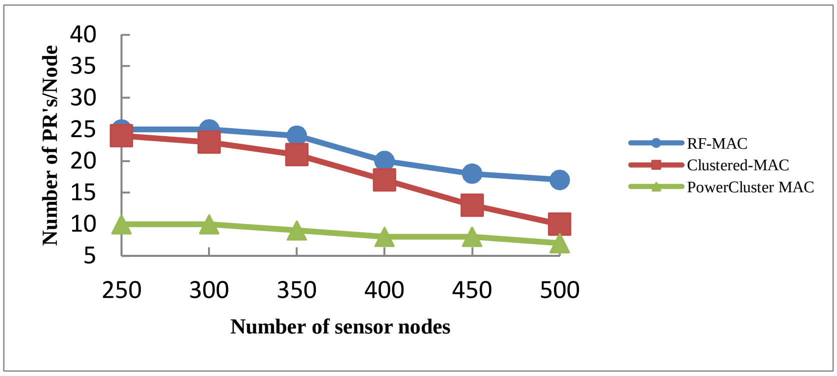

Fig. 6: Effect of node density on Number of Power Request's.

The reason being as the nodes are closer to each other, they are able to scavenge the RF Power requested by the neighbouring nodes.

VII. Conclusion and Future Work:

In this paper, a MAC protocol is proposed for RF rechargeable WSN. The novel idea of using clustering for RF Power transfer is explored in this paper. Simulation results conclude that by using clustering for RF Power transfer, we can minimize the packet loss as well the number of Power Request's and also maintain the network lifetime. Future work will include the effect of dealing with collisions in data as well as RF Power transfer.

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