A WSN Testbed to Enhance Irrigation Techniques Using a Novel Event-Based Routing Protocol

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Abstract— **Due to rapid changes in climatic conditions worldwide, environmental monitoring has become one of the greatest concerns in the last few years. With the advancement in wireless sensing technology, it is now possible to monitor and track fine-grained changes in harsh outdoor environments. Wireless sensor networks (WSN) provide very high quality and accurate analysis for monitoring of both spatial and temporal data, thus providing the opportunity to monitor harsh outdoor environments. However, to deploy and maintain a WSN in such harsh environments is a great challenge for researchers and scientists. Several routing protocols exist for data dissemination and power management but they suffer from various disadvantages. In our case study, there are very limited water resources in the Middle East, hence soil moisture measurements must be taken into account to manage irrigation and agricultural projects. In order to meet these challenges, a WSN that supports a robust, reactive, event-based routing protocol is developed using Ad hoc On-Demand Multipath Distance Vector (AOMDV) as a starting point. A prototype WSN network of 5 nodes is built and a detailed simulation of 30 nodes is also developed to test the scalability of the new system.**

Keywords- wireless sensor networks; reactivity; reliability; soil moisture; rainfall

I. INTRODUCTION

Wireless sensor networks (WSN) are part of a growing technology that has been designed to support a wide range of applications in wireless environments [1][2]. Although sensor networks have been used in various different applications, environmental monitoring is a domain in which they have had a huge impact. Recent climate change-related catastrophes have illustrated the importance of a detailed understanding of the environment and its evolution for the wellbeing of human beings. The capacity of researchers to improve this knowledge is mainly limited by current data collection techniques, which are based on very expensive stations [3]. WSN's are particularly useful in remote or dangerous environments whose behaviors have rarely been studied due to their inaccessibility. Therefore, environmental monitoring is an important area for applying wireless sensor networks [4].

In our study we are using WSN testbed for such harsh environments in Middle East region where the sun is present for at least 12 h per day which makes the climate very dry and hot. One of the biggest problems in the Middle East is the limitation of water resources. We need to measure the soil moisture regularly and very accurately to allow targeted irrigation techniques to be implemented. We are deploying WSN to detect when and where it is raining so that necessary irrigation control measures can be applied.

Many research efforts have tried to deploy WSNs for such environments. But there are many issues with their solutions [3]. Hence in attempting to deploy a WSN successfully in these types of harsh environments and to ensure proper operation of sensor networks we need to resolve following issues.

In order to deal with the harsh environment, it is necessary to build a system which has two main proprieties, i.e., event-driven and robustness. The sensor network should be reactive so that it can detect different events correctly, for example, the presence and the absence of rainfall and hence the changes in degree of moisture in the soil. After the event is detected, the affected nodes need to sample the environment at a much faster rate for example if the system is set to sample after every few minutes when it is not raining then it should sample at few seconds when it is raining. Hence the available bandwidth should be more at nodes affected by rain. Hence the required information is sent across as fast as possible and also accurately to the monitoring center or base station.

Currently there is no such robust and event-based wireless routing protocol to react to such type of outdoor environments. Resource limitations of the sensor nodes and unreliability of low-power wireless links [5], in combination with various performance demands of different applications, impose many challenges in designing efficient communication protocols for wireless sensor networks [6].

In this paper, we discuss the shortcomings of popular routing protocols for our application and we exploit the advantages of the popular routing protocol "Ad hoc On-Demand Multipath Distance Vector" (AOMDV) and modify it to achieve the objectives. To achieve the robustness of wireless sensor network (WSN) this project will enhance the protocol to be an energy aware routing protocol to expand the life time of the nodes. We also discuss in detail the design of a WSN testbed network that can provide all necessary physical parameters to be used in soil moisture and rainfall monitoring algorithms. We implement an algorithm for monitoring and controlling soil moisture events and evaluate the network based on power used, throughput, etc. We deploy an outdoor WSN testbed for testing our algorithm. The rest of the paper is outlined as follows: Section 2 provides a literature review, Section 3 explores a solution approach. Section 4 looks at sensor network design and in Section 5 we provide testbed results and performance. Finally, we conclude in Section 6.

II. Literature Review

There are numerous routing protocols proposed by researchers in this area, to improve performance demands of different applications through the network layer of wireless sensor networks protocol stack [7, 8]. Most of the existing routing protocols in wireless sensor networks are designed based on the single-path routing strategy without considering the effects of various traffic load intensities [9, 10]. In this approach, each source node selects a single path, which can satisfy performance requirements of the intended applications for transmitting its traffic towards the sink node.

Although route discovery through single-path routing approach can be performed with minimum computational complexity and resource utilization, the limited capacity of a single path significantly reduces the achievable network throughput [11, 12]. Therefore, due to the resource constraints of sensor nodes and the unreliability of wireless links, single-path routing approaches cannot be considered effective to meet the performance demands of various applications. In order to cope with the limitations of single-path routing techniques, another type of routing strategy, known as multipath routing, has become a promising technique in wireless sensor and ad hoc networks. Dense deployment of the sensor nodes enables a multipath routing approach to construct several paths from individual sensor nodes towards the destination [13].

Discovered paths can be utilized concurrently to provide adequate network resources in intensive traffic conditions.

In the past decade, the multipath routing approach has been widely utilized for different network management purposes such as improving data transmission reliability, providing fault-tolerance routing, congestion control and Quality of Service (QoS) support in traditional wired and wireless networks.

However, the unique features of wireless sensor networks (e.g., constrained power supply, limited computational capability, and low-memory capacity) and the characteristics of short-range radio communications (e.g., fading and interference [14, 15]) introduce new challenges that should be addressed in the design of multipath routing protocols.

In [7], routing challenges and design issues in wireless sensor networks were discussed. In [16] the researchers provided a brief overview on the existing fault-tolerant routing protocols in wireless sensor networks and categorized these protocols into retransmission-based and replication-based protocols. The researchers in [17] and [18], classified the existing multipath routing protocols in ad hoc networks based on the primary criterion used in their design.

Many routing protocols have been proposed for Wireless Sensor and Ad Hoc Networks. Since we are interested in dynamic and event driven protocol, we studied the likes of AODV, which is a reactive protocol that discovers routes only on the basis of demand using a route discovery mechanism.

It uses traditional routing tables with one entry per destination. The main advantage of AODV [9,10] compared to other routing protocols is that less memory space is required as information of only active routes are maintained, in turn increasing the performance. While on the other side, the disadvantage is; this protocol is not expandable and in large networks, it does not perform well and is not capable to support asymmetric links.

Ad-hoc On-demand Multipath Distance Vector Routing (AOMDV) [19] protocol is an extension to the AODV protocol for computing multiple loop-free and link disjoint paths [20] which aims to remove the disadvantages and the limitation of AODV. The main idea in AOMDV is to compute multiple paths during route discovery. It is designed primarily for highly dynamic ad hoc networks where link failures and route breaks occur frequently. When single path on-demand routing protocol such as AODV is used in such networks, a new route discovery is needed in response to every route break. This inefficiency can be avoided by having multiple redundant paths available. Now, a new route discovery is needed only when all paths to the destination break. AOMDV can also be used to find node-disjoint or link-disjoint routes. But, AOMDV has more message overheads during route discovery due to increased flooding because it is a multipath routing protocol, the destination replies to the multiple RREQs which results in longer overheads.

In [21], researchers improved the performance of standard AOMDV in conditions like mobility or multi communication. They proposed link reliability in route choice. They modified the Route request process to enable reliable paths using Bit Error Rate (BER). They tested the effectiveness of new protocol by considering these improvements under realistic conditions and the result was compared to standard AOMDV and AODV protocols to show improved performance. Researchers in [22] modified AOMDV protocol by proposing a new fuzzy logic based scheme. The proposed protocol was shown to select better paths and increase network survivability. An AOMDV based method (E-AOMDV) was proposed by [23], to conserve energy, find shortest path and for load balancing. In [24], the authors proposed a modified AOMDV protocol called Network Coding-based AOMDV (NC-AOMDV) routing algorithm for MANET. The proposed method tried to increase data transmission reliability and ensure load balancing. An algorithm find maximal nodal remaining energy was proposed in [25], called Delay Remaining Energy for AOMDV (DRE-AOMDV) routing protocol. It claimed to get a solution for finding maximal nodal remaining energy for all routes in selecting a path for end-to-end requirement.

An extension to AOMDV routing protocol was proposed in reference [26]. It was channel adaptive routing protocol to accommodate channel fading. The proposed algorithm was called Channel-Aware AOMDV (CA-AOMDV). It used channel average nonfading duration as routing metric. Using this it selected stable links for path discovery by applying a pre-emptive handoff strategy. A Modified AOMDV (M-AOMDV) Routing Protocol for Maritime Inter-ship Communication [27] was proposed that provides routing recovery mechanism when a link breaks in an active route to reduce lost packets, this will reduce packet loss ratio and delay time.

Another modified version of AOMDV was proposed in [28], called ant-AOMDV or ant colony optimization modification for AOMDV in MANET, in this research the writers uses the modified AOMDV for multipath routing using ant colony for mobile ad hoc networks (MANETs).

Another researcher [29] published a paper about AOMDV-PAMAC, they started their paper explaining that power consumption of nodes in ad-hoc networks is a critical issue, because they operate on batteries, they suggested a new link layer algorithm knows as Power Aware medium Access Control (PAMAC) protocol is proposed which enables the network layer to select a route with minimum total power requirement among the possible routes between a source and a destination.

AOMDV modifications overcomes many limitations of AOMDV but it still has some limitations when used for a real time and robust routing scenario like we have. Thus, we modified AOMDV to suit our purpose and make it more robust, reactive, event driven, and energy aware.

III. Solution Approach

Figure 1 shows the wireless sensor network being deployed over a large geographical area. Each node is able to measure the amount of soil moisture through the soil moisture sensor in the ground as well as detect the presence of rain through the rainfall sensor. The latter is necessary as the amount of soil moisture may not be enough to detect the presence of rain. In addition, the system must quickly react in order to discover over which part of the sensor network is experiencing the event: in this case rain. When rain is detected as falling in a given part of the system, the data is sent from the relevant nodes to a central administrative server or base station through the PC-USB Gateway. We have to change the routing so that information on the change in the soil content in the affected area could be sent to the server as quickly as possible. Hence, this data is routed at a higher priority that other information being sent. Our modified AOMDV protocol works as follows in two schemes. Under the first scheme, the sensor data under normal events (no rainfall) are sampled after every 3h for 10s and sent to the server. During these 3h, the sensors are in sleep mode to save energy and after the data is sampled they again go to sleep mode for another 3h. If we have rainfall event we implement second scheme, in which the data sample is taken after every 1s for the sensor node experiencing the rainfall event, hence the affected nodes send data after every 1s, since the soil moisture may change very rapidly. In second scheme, we also increase the priority of this affected node to transfer data to the base station through the gateway. All the other sensor nodes where there is no rainfall still keep sampling after every 3h. In our previous work [30], we proposed a modified version of the AOMDV protocol. To accommodate these changes dynamically we made changes in the existing AOMDV protocol and proposed a dynamic and robust event driven routing protocol as described below.

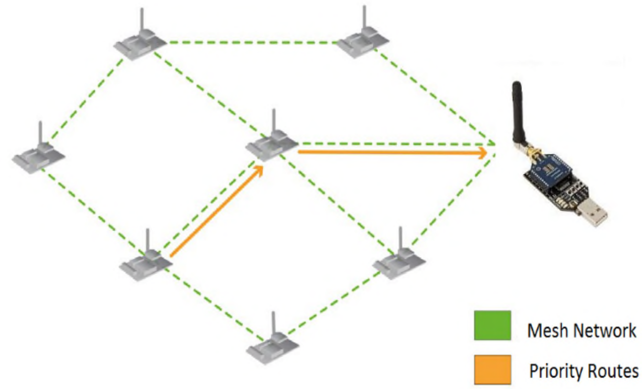

Figure 1. Sensor Network forming mesh.

A. Proposed Changes to AOMDV

The plan is therefore to enhance AOMDV to support a dynamic event-driven system as detailed in this paper. The first issue is that the routes may change due to the change in status of the individual nodes, it is necessary to allow HELLO messages, which are used to detect link changes, to not just monitor links but to fully indicate the status of the node at the other side of the link. So in this case, HELLO messages would also indicate whether or not it is raining on the other end, the network load as well as the power left in the system. A key piece of data is whether or not a node is able to route data on behalf of other nodes. As explained before, if a node is at the center of a downpour, its data is probably more important than the data of its neighboring nodes so it should not route data on behalf of other nodes. In such a situation, the node should also not respond to routing request (RREQ) messages, which are used to discover routes to individual destinations. In addition, though HELLO messages will be sent periodically, it is necessary to have another message type which can be sent immediately in response to sudden environmental, link, or node changes. These messages are called STATUS messages and are sent to neighboring nodes. For example, when a node first detects rain, it will send a STATUS message which is picked up by other nodes. By storing this information from various nodes, it would be possible to detect where the rain is falling in the sensor network.

STATUS messages will cause routes to the central server to be re-evaluated. Let us consider the case depicted in Figure 2. If node A that is not affected by rain, was using a route to the central server via node B and node A, now receives a STATUS message from node B saying that, it has detected rain; then node A, which is not rain-affected, should no longer send data through node B if possible, since, for irrigation purposes, the data being generated by node B is more important. Node A should look for another route back to the server using other non-affected nodes. This would suggest that routes may have priorities based on the importance of the data being routed relative to the data being generated. In this case, node A will downgrade its route through node B, resulting in other routes through non-affected nodes being favored. This is illustrated in Figure 2.

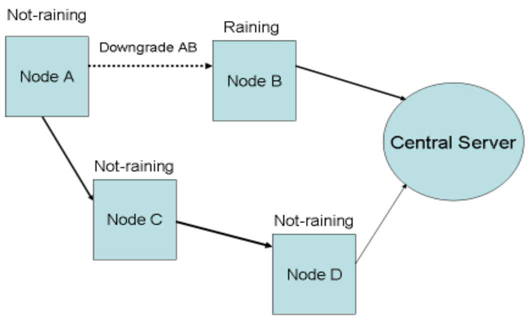

Figure 2. Routing decisions made based on external events.

If both nodes, A and B, detect rain both nodes will send each other their absolute measurements as well as relative changes in the soil moisture content. Nodes with less relative soil moisture content changes which indicate less rain will downgrade routes through regions with high relative soil moisture content changes. So data will be routed away from the most rain-affected areas towards the least rain-affected areas.

C++ language compiler has been used to modify the source code of AOMDV; this modification consists of several enhancements for the current AOMDV protocol. In the following, Algorithm 1, we describes the modification:

Algorithms 1

```
if (event == NO_RAIN)
 begin
      //use standard AOMDV
 end
else
if (event == RAIN)
begin
   sendBrodcastRainPacket(node_id);
   Disable_hello();
   limit_response();
   setPacketPriority(1);
end
else if (event == END_RAIN)
begin
   Enable_Hello();
   replyto_response();
   setPacketPriority(0);
end
```

In the above Algorithm 1, when we detect rain we broadcast “node_id”, disable “hello” messages and set packet priority to 1 for the rain affected node.

When a node is affected by rain it will receive a rain event, this event triggers a rain STATUS broadcast message. Every node that is adjacent to this node will receive this packet. The affected nodes will still send HELLO messages but stop responding to RREQ messages, this will prevent the neighboring nodes from seeing it and sending their data through the affected node. Finally, we implemented a simple priority for the packets that are originated from the affected node; all packets that are sent from this node will have a greater value for its QoS value in the IP header.

If the event ends, the node will return to its normal activity, it will send HELLO packets normally and continue to respond on the RREQ packets and finally sets the QoS value to its normal value.

Algorithms 2

```
if (packet.type == RAIN_PACKET)
begin
   for each(r in routing_table)
   begin
      if (r.nextHop == packet.source)
         remove(packet.source);
   end
end
```

In the above Algorithm 2, when an adjacent node receives a rain packet it will immediately remove all the next hops that this node is involved in. This will prevent any node from sending any data through this node.

IV. SENSOR NETWORK DESIGN

Sensor network design is clearly described in this section as bellow:

A. Monitoring Goals

Our proposed wireless sensor network will be used to monitor spatial variations in soil moisture as well as detect the presence of rainfall over time. Our experimental WSN testbed is set up in Jordan monitored surface soil moisture and presence of rainfall. Our long-term objective is to monitor soil moisture regularly so as to implement targeted irrigation techniques. The data we gather from our system will also be used for managing the irrigation resources throughout Jordan by providing improved guidelines for the Jordan irrigation management model.

The reactivity of the system should be also very high to detect the occurrence of the event as soon as possible, as in this case, rainfall. When such an event is detected the data or sensor readings should be sent to the base station reliably and quickly and for this reason we need to select the right routes. This data should be sent to the base station at a higher priority than all other data being sent [30].

Wireless systems are likely to face errors as the environment in which these sensors are deployed are harsh environments, which might have severely dry conditions and can affect their performance. Hence we need a very reliable system which ensures that information is correctly and accurately routed to the base station. The sensor network must also ensure heavy data flow in case of rainfall so that no routes or links are overwhelmed with data. We need to

ISBN: 978-1-61208-572-2

manage the information flow and to also reduce redundancy from data to reduce traffic.

Finally, since there are always energy crises in the case of wireless sensor networks, we need to carefully plan each activity to maximize battery life also take advantage of the high duration of sunlight available in the Middle East Region. Hence we make use of the solar-powered WSN nodes by which the problem is somewhat lessened. We still need power management as a lot of data will be sent when a wireless node is experiencing rainfall and it needs to send a lot of information and a lot of power will be required at this time. Hence, the sensor network needs to strike a perfect balance and trade-off between the power left and the information required to be sent.

We are using ZigBee medium range communication module standard, which is based on the IEEE 802.15.4 [31], which has a lot of advantages such as: consumes less power, also saves power as it has sleep mode, has a large capacity network, is more reliable and has low cost of related components [32,23]. The authors in [33] have proposed to reduce energy consumption by using a routing algorithm, which is a combination of Ad hoc On-Demand Distance Vector Routing Junior and the Cluster-Tree technique. However, there is no practical implementation for all these research initiatives. In our system, power is directly saved by using priority based routing algorithm hence reducing the data at times of raining event when many data is produced. However, even after raining data should be sampled more frequently in order to keep track of the soil moisture.

B. *WSN Architecture*

At each sensor nodes, we have a soil moisture sensor and rainfall sensor attached to it. Our sensor network is based on Libelium Waspmotes sensor nodes and ATmega1281rds Microcontroller [34]. It is connected to following components:

- Wireless Interface (Waspmote XBee based on IEEE 802.15.4 standard)
- Soil moisture sensor (Watermark 200SS)
- Rainfall sensor (Libelium Weather Station WS 3000)
- USB-PC Interface (Waspmote Gateway)
- Solar Panel (Waspmote rigid solar panel 7 V-500 mA)
- 6600 mA Li-Ion rechargeable batteries

The current network deployment has four sampling nodes, but more generally, the architecture supports many nodes [34].

Zigbee RF nodes are used as communication models to transmit the sampled data to the gateway; these can have the best average lifetime of 8 years using dual batteries 3 V, at 3000 mAh. Some studies like [31], show that ZigBee model based on IEEE 802.15.4 standard with correct topology can last up to 10 years. Hence, we are using ZigBee communication model for our research.

C. *WSN Working Principle*

The objective of our research is to provide a dynamic and robust event driven protocol for soil moisture monitoring so that the results can be used in the future to manage irrigation resources throughout Jordan. We use a mesh topology for network connectivity because of its advantages in our application scenario. Mesh topologies are able to route data and messages to the final gateway node through several different nodes. Even if the connection to any RF node is lost because of any environmental tragedy or loss of power, etc. still all the important data can reach to the gateway node and the base station due to the mesh topology.

D. *Hardware Design*

1) Sensor Nodes: We are using Waspmote WSN as shown in Figure 3, which is an open source wireless sensor platform the speciality of which is implementing sensor nodes having low power consumption capability [31]. Hence, our sensor nodes can work autonomously, working on battery power and having a maximum lifetime of 7–8 years [35] based on the cycle of operation, communication protocol and the communication module used.

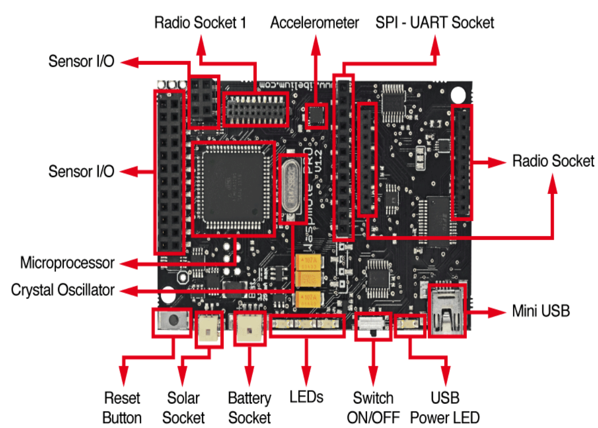

Figure 3. Waspmote Sensor Node.

This RF module has a long range of 7000 m but lower power consumption than Wi-Fi (802.11). It operates at a very low data rate of 250 kbps at 2.4 GHz [36,37]. These modules have mechanism to extend battery life by using sleep modes.

2) Soil Moisture Sensor: The Soil Moisture Sensor Watermark 200SS [38] developed by Irrometer, as shown in figure 5, is one of the most important component in our research. It has very satisfactory features like stable calibration, a measurement range from 0 to 239 cb (kPa), it has no soil dissolvability, can withstand freezing temperatures, and is low cost and low maintenance [38].

3) Rainfall Sensor: The rainfall sensor is a part of the Weather Station WS-3000, shown in Figure 5, which comprises of an anemometer, a wind vane, and a pluviometer [39]. The Weather Station is placed above ground on a pole and connected to the WSN sensor node. Our study is only concerned about pluviometer readings which provides a digital signal whose frequency is directly proportional to the intensity of rainfall.

Figure 4. Watermark Soil Moisture Sensor and Weather Station having Rainfall Sensor.

V. TESTBED AND SIMULATION RESULTS

The primary goal for this section is to clarify testbed setup and result for simulation and testbed.

A. *WSN Testbed Setup*

We setup our testbed in a garden in Jordan. The current network deployment has five nodes, which are 5 m apart from each other, but more generally, the architecture supports many nodes [15].

The setup of this scenario consists of 5 wireless nodes from node 0 (N0) to node 3 (N3), as shown in Figure 6 and one gateway node (GW) which is connected to the server. We will have two constant bit rates (cbr) streams, one from node 0 and the other from node 2. The destination for both streams will be gateway node (GW). We will call them cbr0 and cbr2 respectively. According to AOMDV protocol, cbr2 traffic will go from node 2 to node 0 then node GW, and cbr0 traffic will go to node GW directly. Node 2 traffic, cbr2 will go through two paths, the primary one through node 0 and the secondary through node 1. After three hours during sending packets, node 0 is affected by RAIN (which is the event).

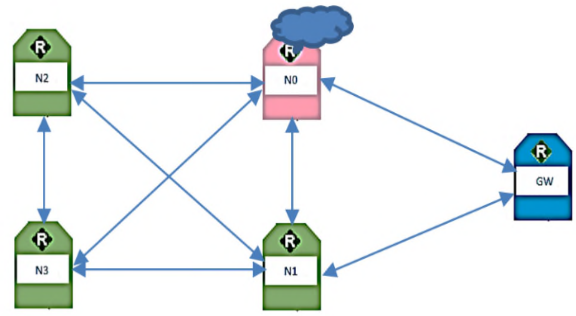

Figure 5. Five Node wireless sensor network (WSN) Test Bed Setup.

Tables I and Table II show the result of routing table before and after rain is detected at node 0, the routing table for node 2 and 3 has been changed which take another route through node 1 instead of the primary one through node 0 to send data to GW (destination) because node 0 is affected by RAIN. Hence, node 0 has very important data (soil moisture) and it has to send it first and should take the highest priority to send data.

TABLE I. TABLE BEFORE RAIN BEING DETECTED AT NODE 0

N0		
Dest No	**Nxt hop**	**Hop cnt**
3	3	1
GW	GW	1
1	1	1
2	2	1

N1		
Dest No	**Nxt hop**	**Hop cnt**
3	3	1
GW	GW	1
2	2	1
0	0	1

N2		
Dest No	**Nxt hop**	**Hop cnt**
3	3	1
1	1	1
0	0	1
GW	1	2
	0	2

N3		
Dest No	**Nxt hop**	**Hop cnt**
1	1	1
2	2	1
0	0	1
GW	1	2
	0	2

GW		
Dest No	**Nxt hop**	**Hop cnt**
0	0	1
1	1	1
2	0	2
	1	2
3	0	2
	1	2

TABLE I. ROUTING TABLE AFTER RAIN BEING DETECTED AT NODE 0

N0		
Dest No	**Nxt hop**	**Hop cnt**
3	3	1
GW	GW	1
1	1	1
2	2	1

N1		
Dest No	**Nxt hop**	**Hop cnt**
3	3	1
GW	GW	1
2	2	1
0	0	1

N2		
Dest No	**Nxt hop**	**Hop cnt**
3	3	1
1	1	1
0	0	1
GW	1	2

N3		
Dest No	**Nxt hop**	**Hop cnt**
1	1	1
2	2	1
0	0	1
GW	1	2

GW		
Dest No	**Nxt hop**	**Hop cnt**
0	0	1
1	1	1
2	1	2
3	1	2

B. Simulation Setup

To show that our proposed protocol is also expandable we used simulation tools for 5 nodes scenario and for a very large scenario consisting of 30 nodes. The source code of the simulation is written in TCL language and runs the simulation example on ns-2.35 Linux Ubuntu version 12.

For 5 node setup, we use standard AOMDV in first period from 0 to 900 in second one from 900 to 2000 we use the modified version of AOMDV.

An AWK script was built to calculate the average of Throughput and End to End Delay on node 0 and node 1 before and after node 1 is affected by raining. The highest priority data stream will grant to cbr1 coming from node 1 because it affected by rain and it has important data that should be send to the destination node 2. Rerouting cbr0 coming from node 0 traffic through node 4, which has data with low priority. In this way we reduce forwarding load on node 1 that means the throughput and end to end delay will be better on cbr1 after node 1 affected by rain.

For the complex scenario consisting of 30 nodes, we calculate that 5 out of 30 nodes were affected by rain and measure the performance and the energy consumption.

There are 30 wireless nodes from node 0 to node 29 distributed with fixed location across the testbed as shown in Figure 7. We will have two constant bit rates (cbr) streams one from node 0 and one from node 1 the destination for both streams will be node 29 (GW) we will call them cbr0 and cbr1 respectively. According to AOMDV, protocol cbr0 traffic will go through the path node 0 -> node 1 -> node 2 -> node 13 -> node 4 -> node 15 -> node 6 -> node 17 -> node 18 then node 29, and cbr1 traffic will go through the same path.

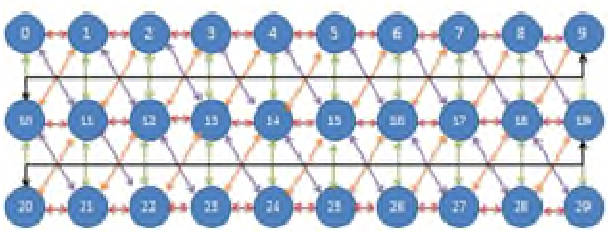

Figure 6. 30-Nodes Simulation Setup.

The five nodes which are affected by rain are 1, 12, 16, 21, 25. This means that node 0 or 1 will use secondary paths when any node in the primary path is affected by RAIN.

Simulation time is 2500 ms, we set up the constant bit rate (cbr) with variable rate values depending on rain level. For example, when it is raining lightly, the (cbr) rate will be 0.05 Mbps, when rain becomes heavier, the (cbr) rate changed to 0.1 Mbps and, finally, when flood occurs, the (cbr) rate changes to 0.5 Mbps. Packet size for all (cbr) is 1000 byte.

C. Performance Measurements

1) Performance Measurements for 5 Node Simulation Setup

The results listed in Table III clearly show improvement of Throughput and End to End Delay on cbr0 coming from node 0 which validate our assumptions and it showing that the event-driven approach does improve overall network efficiency.

TABLE II. PERFORMANCE MEASUREMENT BEFORE AND DURING THE TIME WHEN NODE 0 IS AFFECTED BY RAIN.

Type/protocol and Time	Standard AOMDV 3 hours Before Rain	Modified AOMDV 3 hours After Rain
Total Sent Size From cbr2	5000 kbit	3749 kbit
Total Sent Size From cbr0	4375 kbit	6874.7 kbit
End-to-End Delay (cbr2)	256910 ms	349410 ms
End-to-End Delay (cbr0)	16210 ms	5.67 ms
Throughput (cbr2)	2.65 kbps	3.70 kbps
Throughput (cbr0)	4.20 kbps	6.20 kbps

2) Performance Measurements for 30 Node Simulation Setup

Before rainfall, we used the standard AOMDV protocol and after the rainfall, we used our modified AOMDV protocol to compare its performance with the standard AOMDV. In this simulation scenario we divided the simulation period depending on raining level, for instance with no rain the period from 0 to 900 s, light rain period from 900 to 2000 s and heavy rain from 2000 to 2500 s.

Node 1 is affected by two levels of rain light rain and heavy rain, so we compared the Throughput and End to End Delay in two levels.

The results listed in Table IV clearly show improvement in Throughput and End to End Delay on cbr1 coming from node 1 which validates our assumptions and it shows that the event-driven approach does improve overall network efficiency.

TABLE III. PERFORMANCE MEASUREMENT BEFORE AND DURING THE TIME WHEN NODE 1 IS AFFECTED BY RAIN.

Type/Rain-Level (Time)	Light rain - 0.05Mbps (0 – 900) s	Heavy Rain - 0.1Mbps (900 – 2000) s	Very Heavy flood - 0.5 Mbps (2000 – 2500) s
Total Sent Size From cbr0	5000.1 kbit	6875.4 kbit	18746 kbit
Total Sent Size From cbr1	4375 kbit	13748.7 kbit	18750.2 kbit
End-to-End Delay (cbr0)	18.78 ms	18.79 ms	4465.59 s
End-to-End Delay (cbr1)	16.62 ms	16.50 s	16.42 ms
Throughput (cbr0)	5.56 kbps	6.25 kbps	3.75 kbps
Throughput (cbr1)	4.86 kbps	12.50 kbps	37.50 kbps

Figure 7 shows the throughput of Node 1, separately being affected by rain. The reason behind this increase in throughput is that at heavy and very heavy rain, we use the modified AOMDV protocol.

 ISBN: 978-1-61208-572-2

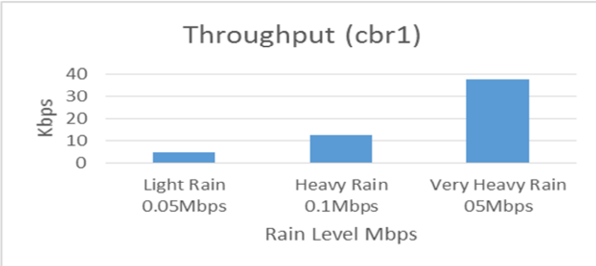

Figure 7. The throughput differences between light rain, heavy and very heavy rain, on node 1.

D. Energy Consumption

We measure the energy consumption in three modes for each sensor node, idle mode, receiving mode and transmitting mode. The energy consumed in idle mode is called idle energy (Idle Energy). The energy consumed by a node in transmission of data is called transmission energy (Trans Energy) and the energy consumed by a node to receive data is called receiving energy (Rec Energy).

When a node is affected by rain it will receive a rain event, this event triggers a special broadcast rain packet called STATUS message. Every node that is adjacent to this node will receive this packet. The affected nodes will still send HELLO messages but stop responding to RREQ messages, this will prevent the neighboring nodes from seeing it and sending their data through the affected node.

Hence, the nodes affected by rainfall will not receive any packets from other nodes and hence they will require very less receiving energy, on the other hand, they will just have their own data to transmit, hence the transmission energy also decreases.

1) Energy Consumption for 5 Node WSN Testbed

The Waspmotes consumes 15mA of energy per hour in switched on state and just consumes 55µA of energy per hour in sleep state [40]. We have designed our protocol to be energy-efficient. In our protocol sensor, data under normal events are sampled for 10s after every 3h and sent to the server. When we measured energy consumption for our protocol it was found that, it only consumes 0.004 mA of energy per hour. If we have a rainfall event, we implement second scheme under which we sample the data for 10s after every 10s, only for the sensor node experiencing the rainfall event, since the soil moisture may change very rapidly. In second scheme, when there is a rainfall our protocol consumes only 0.042 mA of energy per hour for the effected node, which is also very less than the default energy consumption of 15 mA per hour for the Waspmote [40]. Hence, our protocol is also energy efficient.

As shown in Tables V and VI the energy measurements in mA taken after rainfall when we use modified AOMDV, are less than those taken before rainfall when we use standard AOMDV, for both received energy (Rec Energy) as well as transmission energy (Trans Energy) because the nodes affected by rainfall will not receive any data from other nodes and hence they will require very less receiving energy, on the other hand they will just have their own data to transmit, hence the transmission energy also decreases. We also show these results in Figures 8 and 9.

TABLE V. ENERGY MEASUREMENT BEFORE NODE 0 AFFECTED BY (AOMDV).

Node No	Idle_Energy mili Ampere	Rec_Energy mili Ampere	Trans_Energy mili Ampere
GW	0.0275	3.75	3.75
0	0.0272	4.35	3.1
1	0.0271	4.33	3.3
2	0.0269	3.21	4.31
3	0.0270	3.31	4.35

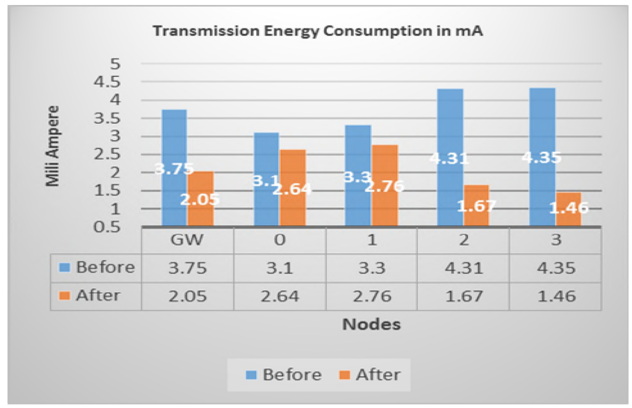

Figure 8. Transmission Energy Consumption in mA.

TABLE IV. ENERGY MEASUREMENTS DURING RAINFALL ON NODE 0 (MODIFIED AOMDV).

Node No	Idle_Energy mili Ampere	Rec_Energy mili Ampere	Trans_Energy mili Ampere
GW	0.0275	4.21	2.05
0	0.0265	1.02	2.64
1	0.0260	3.01	2.76
2	0.0245	1.82	1.67
3	0.0210	1.79	1.46

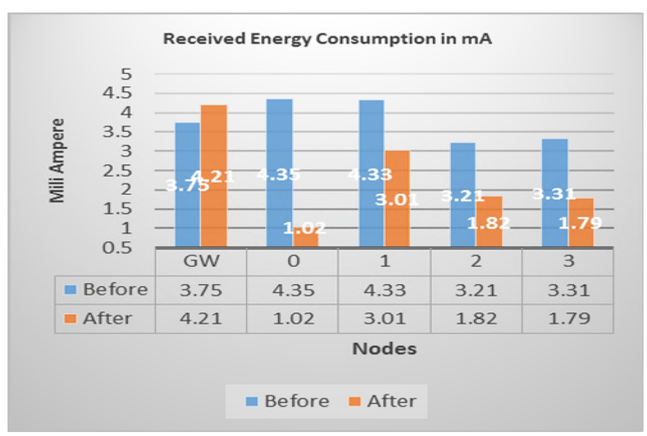

Figure 9. Received Energy Consumption in mA.

2) *Energy Consumption for 30 Node Simulation Setup*

This section of our paper is concerned about the energy, consumptions for all nodes before the nodes are affected by rain, when the nodes will use the standard version of AOMDV and after the nodes are affected by rain when they will use the modified version of AOMDV, the calculation of total energy has been done during the simulation periods for each cases before and after the nodes affected by rain.

The total energy consumed has been calculated for all nodes before and after the nodes were affected by rain for the three simulations. In addition, we calculated the rate of decrease in consumed energy before and after the nodes are affected by rain.

TABLE V. ENERGY MEASUREMENTS BEFORE NODE 1 IS AFFECTED BY RAIN.

Node No.	Total_Energy (joules)	Idle_Energy (joules)	Tran_Energy (joules)	Rec_Energy (joules)
1	218940000.00	191000000.00	4140000.00	23800000.00
12	35506380.00	30100000.00	26380.00	5380000.00
16	35726423.20	29300000.00	26423.20	6400000.00
21	23737540.90	20700000.00	17540.90	3020000.00
25	23817550.60	19100000.00	17550.60	4700000.00

Tables VII and VIII clearly show that of consumption energy for affected nodes before is greater than energy consumption after rainfall starts. As we can see from the 'Total' columns in both tables, the total energy consumed decreases for all the nodes and the decrease in energy is much greater for the nodes affected by rainfall. The idle energy, transmission energy as well received energy decreases for all the nodes. The largest decrease in total energy is due to the decrease in transmission energy.

TABLE VI. ENERGY MEASUREMENTS DURING RAINFALL ON NODE 1.

Node No.	Total_Energy (joules)	Idle_Energy (joules)	Tran_Energy (joules)	Rec_Energy (joules)
1	140710000.00	123000000.00	1310000.00	16400000.00
12	23851969.88	20300000.00	1969.88	3550000.00
16	27722152.14	22800000.00	2152.14	4920000.00
21	15771225.74	13800000	1225.74	1970000
25	16011241.87	12900000	1241.87	3110000.00

We calculate total energy consumed by all the nodes that are affected by rainfall.

The total energy for node (k) =

$$idle\_energy\ (k) + trans\_energy(k) + recv\_energy(k)$$

The total energy for all affected nodes =

$$\sum_{k=0}^{n} \text{idle\_energy}(k) + trans\_energy(k) + recv\_energy(k)$$

We calculated the total consumed energy for all affected nodes before rains as = T-energy-before = 337727894.70

And total consumed energy for all affected nodes after rains = T-energy-after = 224066589.63

Therefore the consumed energy decreasing rate = (T-energy-before/ T-energy-after) %

Rate of decrease in Consumed energy (affected nodes) = 51%

We can clearly observe that the energy consumptions for all nodes affected by rain has decreased sharply as shown in Figure 11, also the energy consumptions on all nodes has decreased.

The above figure is showing energy consumption by 5 nodes before and after they are affected by rain. Again our modified AOMDV clearly outperforms the standard AOMDV in terms of energy consumption.

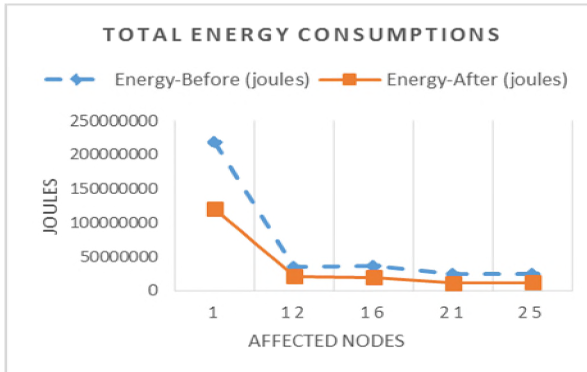

Figure 10. Energy consumed by nodes before and during rainfall.

VI. CONCLUSIONS

This paper outlined design, deployment and evaluation of our reactive, robust and enhanced version of AOMDV protocol. Our event driven enhancements mean that our protocol not only increases the performance but also makes it energy efficient as the energy consumption is considerably reduced for the nodes experiencing the rainfall and also in general because we use the sleep mode when it is not raining. We also successfully showed in simulation results that our enhanced AOMDV protocol is scalable. We compared its performance with prior AOMDV protocol. For our proposed protocol the results clearly show that it reduces average delay while at the same time increases the throughput of the nodes being affected by rain. The enhanced throughput and low delay clearly indicates that the proposed changes to AOMDV to support events such as rain would be a significant and meaningful addition to AOMDV, which can be used in several WSN applications.

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