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Initiative Determination Procedure of Cross-Layer Protocol in Wireless Sensor Networks

Murali Ponaganti[#1]
[#]*Department of Computer Science*
& JNTU University
[1]murali.ponaganti@yahoo.com

T.P.Shekar[#2]
[#]*Department of Computer Science*
& JNTU University

D.Sagar[#3]
[#]*Department of Computer Science*
& JNTU University

Abstract— **Wireless sensor networks (WSNs) are event-based systems that develop the communal attempt of densely deployed sensor nodes and incessantly observe a certain physical phenomenon. The majority of the communication protocols are individually developed and optimized for different networking layers, i.e., transport, network, medium access control (MAC), and physical layers. While these protocols achieve very high performance in terms of the metrics related to each of these individual layers, they are not jointly designed and optimized to maximize the overall network performance while minimizing the energy expenditure. The design principle of XLP is based on the cross-layer concept of initiative determination, which enables receiver-based contention, initiative-based forwarding, local congestion control, and distributed duty cycle operation to realize efficient and reliable communication in WSNs. The initiative determination requires easy comparisons against thresholds, and thus, is very simple to implement, even on computationally constrained devices. XLP significantly improves the communication performance and outperforms the customary layered protocol architectures in terms of both network performance and completion complexity.**

Keywords—**Cross-layer protocol, congestion control, routing, medium access control, wireless sensor networks.**

I. INTRODUCTION

WIRELESS sensor networks (WSNs) major objective is to dependably detect/estimate event features from the shared information provided by sensor nodes respecting their limited power, storage space, and processing capabilities. To this conclusion, there have been a important figure of investigate efforts that aim to expand joint networking protocols to achieve communication with utmost energy efficiency. WSNs are event-based systems that exploit the collective effort of densely deployed sensor nodes and incessantly watch a certain physical phenomenon.

Clearly, there is still much to be gained by rethinking the functionalities of protocol layers in a unified way so as to provide a single message module for efficient communication in WSNs. To this end, this paper introduces a novel concept, i.e., initiative determination, and illustrates how certain traditional networking functionalities can be jointly designed based on this concept to implement a cross-layer process of medium access, distributed routing, and restricted overcrowding control functionalities. The plan determination procedure is used for each node to decide on participating in communication based on its present state related to link quality, location, current traffic load, buffer level, and remaining energy level. These basic process states are incorporated into a unified decision incentive to define a node's level of willingness in participating in the communication. Accordingly, a cross-layer protocol (XLP)

is developed to achieve efficient and reliable event communication in WSNs with minimum energy expenditure. In a cross layer simulation platform, the state-of-the-art layered and cross-layer protocol configurations have been implemented along with XLP to provide a complete performance evaluation. Analytical performance evaluation and simulation experiment results show that XLP significantly improves the communication performance and outperforms the traditional layered and recent cross-layer protocol architectures in terms of both network performance and implementation complexity. These results highlight the advantages of the initiative concept, which is a novel perspective for networking in WSNs.

A cross-layer protocol (XLP) is introduced, which achieves congestion control, routing, and medium access control in a cross-layer fashion. The design principle of XLP is based on the cross-layer concept of initiative determination, which enables receiver-based contention, initiative-based forwarding, local congestion control, and distributed duty cycle operation to realize efficient and reliable communication in WSNs. XLP is the first protocol that integrates functionalities of all layers from PHY to transport into a cross-layer protocol XLP significantly improves the communication performance and outperforms the traditional layered protocol architectures in terms of both network performance and implementation complexity.

II. CROSS-LAYER PROTOCOL FOR WSNs

The design principle of XLP is a unified cross layering such that both the information and the functionalities of three fundamental communication paradigm (medium access, routing, and congestion control) are considered in a single protocol operation. Consequently, XLP incorporates the required functionalities by considering the channel effects. The details of these functionalities are explained in the following sections. Before explaining the specifics of the XLP operation, we first introduce the initiative determination concept, which constitutes the core of the XLP.

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2.1 Initiative Determination:-

The initiative determination concept coupled with the receiver-based contention mechanism provides freedom to each node participating in communication. In WSNs, the major goal of a communication suite is to successfully transport event information by constructing (possibly) multihop paths to the sink. To this end, the cross-layer initiative determination concept constitutes the core of the XLP and implicitly incorporates the intrinsic communication functionalities required for successful communication in WSNs.

Consider a node, i, which initiates transmission by informing its neighbors that it has a packet to send. This is achieved by broadcasting a request to send (RTS) packet. This decision is made through the initiative determination based on the current state of the node. The initiative determination is a binary operation where a node decides to participate in communication if its initiative is 1.The major goal of a communication suite is to successfully transport event information by constructing (possibly) multihop paths to the sink. To this end, the cross-layer initiative determination concept constitutes the core of the XLP and implicitly incorporates the intrinsic communication functionalities required for successful communication in WSNs.

$$I = \begin{cases} 1, \ if \begin{cases} \mathcal{E}RTS \geq \mathcal{E}Th \\ \lambda_{relay} \leq \lambda_{relay}^{Th} \\ \beta \leq \beta^{max} \\ E_{rem} \geq E_{rem}^{min} \end{cases} \\ 0, \qquad Otherwise \end{cases} \quad (1)$$

The initiative is set to 1 if all four conditions in (1) are satisfied, where each condition constitutes certain communication functionality in XLP. The first condition, i.e., ∑RTS ≥Th, ensures reliable links to be constructed for communication based on the current channel conditions. For this purpose, it is required that the received signal-to-noise ratio (SNR) of an RTS packet, _RTS, is above some threshold ∑Th for a node to participate in Communication. The effect of this threshold on routing and energy consumption performance will be analyzed and the most efficient value of this threshold. The second, i.e., $\lambda_{relay} \leq \lambda^{Th}_{relay}$ relay, and the third, i.e., $\beta \leq \beta^{max}$, conditions are used for local congestion control in XLP. The third condition ensures that the buffer occupancy level of a node, β, does not exceed a specific threshold, β^{max}, so that the node does not experience buffer overflow and the congestion is prevented. The last condition, i.e., $E_{rem} \geq E^{min}_{rem}$, ensures that the remaining energy of a node E_{rem} stays above a minimum value, E^{min}_{rem}. This constraint helps preserve uniform distribution of energy consumption throughout the network.

2.2 Basics, Definitions, and Network Model

Assume the following network model for the operation of XLP: Each node performs a distributed duty cycle operation such that the transceiver circuit of the node is on for a certain fraction of the time and is switched off for the remaining fraction of the time during which the sensors can still sample data. The on-off periods are managed through a duty cycle parameter, which defines the fraction of the time a node is active. More specifically, each node is implemented with a sleep frame with length TS sec. A node is active for TS sec and is asleep state for sec. Note that the start and end times of each node's sleep cycle are not synchronized. Consequently, a distributed duty cycle operation is employed. Furthermore, we assume that each node is aware of its location. This assumption is motivated by the fact that WSN applications inherently require location information to associate the observed information by each node to a physical location. Hence, each node is required to be aware of its location, which can be provided through either an onboard GPS or a localization algorithm. Thus, it is only natural to leverage this information for communication. The network model is also geared toward event-based information flow, where nodes send information to a single stationary sink if an event occurs in their vicinity. The area that an event occurs is denoted by the event area and the nodes in this area generate event information. Based on this network model, the protocol operation details are explained in the following sections according to Fig. 1.

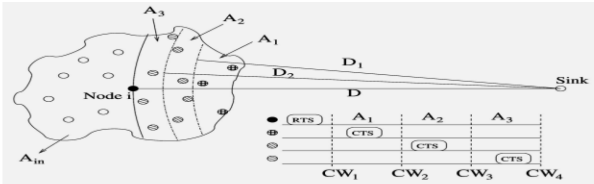

Fig. 1. Priority regions and the prioritization mechanism.

2.3 Transmission Initiation

When a node *i* has a packet to transmit, it first listens to the channel for a specific period of time. If the channel is occupied, the node performs back off based on its contention window size, CWRTS. When the channel is idle, the node broadcasts an RTS packet, which contains the location information of itself and the sink. A node which receives a packet first checks if it is inside the feasible region. To save energy, nodes inside the infeasible region switch to sleep for the duration of the communication.

2.4 Receiver Contention

Each priority region, A_i, corresponds to a backoff window size, CW_i. Based on its location, a node backs off For $\sum^{i-1}_{j=1} CW_j + cw_i$, where cw_i is randomly chosen such that cw_i€[0, CW_{max}], where $CW_{max} = CW_i - CW_{i\_}$. This back off scheme helps differentiate nodes of different progress into different prioritization groups. Only nodes inside the same group contend with each other. It determines that another potential receiver j with a longer progress has accepted to forward the packet and node k switches to sleep for the duration of the communication.

When node *i* receives a CTS packet from a potential receiver, it determines that the receiver contention has ended and sends a DATA packet with the position of the winner node in the header. The CTS and DATA packets both inform the other contending nodes about the transmitter-receiver pair. It may happen that multiple CTS packets from the same priority region can collide and a node from a lower priority region can be selected. XLP does not try to resolve this problem as this probability is very low since the contention region is already divided into multiple regions and the cost of trying to resolve this outweighs the gains.

2.5 Angle-Based Routing

Since the routing decisions depend, in part, on the locations of the receivers, there may be cases where the packets reach local minima. In other words, a node may not find any feasible nodes that are closer to the sink than itself. This problem is known as a communications void in geographical routing-based approaches and is generally resolved through face routing techniques [1],[3],[4], [5], [6], [7], [8]. Although localized, face routing necessitates a node to communicate with its neighbors to establish a planarized graph and construct routes to traverse around the void. This requires information exchange between the neighbors of a node. Since this communication increases the protocol overhead, we introduce a stateless solution to face routing, i.e., angle-based routing technique.

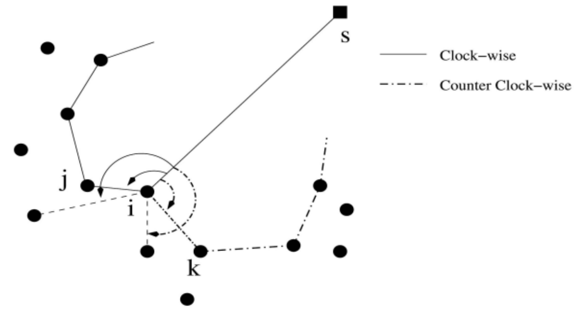

Fig. 2. Illustration of angle-based routing.

The main principle of angle-based routing can be seen in Fig. 2. When a packet reaches node i, which is a local minimum toward the sink, the packet has to be routed around the void either in clockwise direction (through node j) or in counterclockwise direction (through node k). Assume that lines are drawn between node i and sink s, as well as between node i and its neighbors. If we compare the angles between line i; s, and the other lines, angle s_{ij} (angle ffsik) has the smallest angle in the counterclockwise (clockwise) routing direction. Using this geometric property, routes can be constructed around the void. Once a direction is set (clockwise or counterclockwise), the packet traverses around the void using the same direction. Hence, for angle-based routing, we introduce the term traversal direction to indicate this direction. Note that clockwise (counterclockwise) traversal direction refers to the traversal direction of the packets rather than the way the angles are measured.

2.6 Local Cross-Layer Congestion Control

XLP incorporates a new hop-by-hop local cross-layer congestion control component, which is devised based on the buffer occupancy analysis presented here. The objective of this component is to perform hop-by-hop congestion control by exploiting the local information in the receiver contention and avoid the need for end-to-end congestion control. It also exploits the local reliability measures taken by the channel access functionality, and hence, does not necessitate traditional end-to-end reliability mechanisms.

The overall input packet rate at node i, λ_i, can be represented as

$$\lambda_i = \lambda_{ii} + \lambda_{i,relay} = \lambda_{ii} + \sum \lambda_{ji} \qquad (2)$$

receives relay packets, and $\lambda_{i;relay}$ is the overall relay packet rate of node i. Node i aims to transmit all the packets in its buffer, and hence, the overall output rate of node i is given by

$$\mu_i = (1 + e_i)(\lambda_{ii} + \lambda_{i,relay}) \qquad (3)$$

Where e_i is the packet error rate and 1+ e_i is used to approximate the retransmission rate since the routes are selected by considering a high SNR value through the initiative determination process. Note that, since the node retransmits the packets that are not successfully sent, the output rate is higher than the input rate.

According to (2) and (3), in a long enough interval, T_α, the average time the node i spends in transmitting and receiving, is given by

$$T_{rx} = \lambda_{i,relay} T_\infty T_{PKT}$$
$$T_{tx} = (1 + e_i)(\lambda_{ii} + \lambda_{i,relay}) T_\infty T_{PKT} \quad (4)$$

Respectively, where TPKT is the average duration to transmit a packet to another node including the medium access overhead.

To prevent congestion at a node, the generated and received packets should be transmitted during the time the node is active. Because of the duty cycle operation, on average, a node is active δT_α sec. Therefore,

$$\delta T_\infty \geq [(1 + e_i)\lambda_{ii} + (2 + e_i) T_\infty T_{PKT} \quad (5)$$

Consequently, the input relay packet rate, λ_i; relay, is bounded by

$$\lambda_{i,relay} \leq \lambda^{Th}_{i,relay} \quad (6)$$

Where the relay rate threshold, λ^{Th}_{relay} is given by

$$\lambda^{Th}_{i,relay} = \frac{\delta}{(2+e_i) T_{PKT}} - \frac{(1+e_i)}{(2+e_i)} \lambda_{ii} \quad (7)$$

In case of congestion, the XLP node reduces the rate of generated packets λ_{ii} multiplicatively, i.e., $\lambda_{ii} = \lambda_{ii}$, 1/ν where ν is defined to be the transmission rate throttle factor. If there is no congestion detected, then the packet generation rate can be increased conservatively to prevent oscillation in the local traffic load. Therefore, the XLP node increases its generated packet rate linearly for each ACK packet received, i.e., $\lambda_{ii} = \lambda_{ii} + \infty$. XLP adopts a rather conservative rate control approach mainly because it has two functionalities to control the congestion for both the source and the router duties of a sensor node. As the node decides to take part in the forwarding based on its buffer occupancy level and relay rate, it already performs congestion control as a part of the XLP's forwarding mechanism. Hence, the XLP node does not apply its active congestion control measures, i.e., linear increase and multiplicative decrease, to the overall transmission rate. Instead, only the generated packet rate, λ_{ii} is updated.

2.7 XLP Duty Cycle Analysis

To successfully transmit the packet, a pair of nodes needs to complete the four-way handshaking. Assume that the distance between the pair of nodes is d_h=E[d_{next}_hop]. Moreover, the probabilities to successfully receive a data packet and a control packet at this distance are $p^D_s(d_h)$ and $p^C_s.(d_h)$, respectively.4 When a transmitter node sends an RTS packet, it is received by the receiver node with probability $p^C_s.(d_h)$ and the node replies with a CTS packet. If the CTS packet is received (also with probability $p^C_s.(d_h)$, the transmitter node sends a DATA packet, and the communication is concluded with an ACK packet. In every failure event, the node begins retransmission. Therefore, the expected energy consumed by the transmitting node, E_{TX}, is

$$E_{TX} = \frac{K}{(p_s^c)^3 p_s^D} \quad (8)$$

Where

$$K = E_{sense} + (p_s^c)^2 \left[E_{tx}^R + E_{Wait}^C + E_{rx}^C\right] + \left(1 - (p_s^c)^2\right) E_{t/o}^C + (p_s^c)^3 p_s^D \left[E_{tx}^D + E_{tx}^A\right] + (p_s^c)^2 (1 - p_s^c p_s^D) E_{t/o}^A$$

III. PERFORMANCE EVALUATION

The following performance metrics: *Throughput* is thenumberof bits per second received at the sink. In calculating this metric, only unique packets are considered since multiple copies of a packet can be received at the sink for certain protocols.

Goodput is the ratio between the total number of unique packets received at the sink and the total number of packets sent by all the source nodes. As a result, the overall communication reliability of the suites is investigated.

Energy Efficiency is the most important metric in WSNs. We consider the average energy consumption per unique packet that is received at the sink, which can be considered the inverse of energy efficiency. Hence, a lower value refers to a more energy-efficient communication.

Number of Hops is the number of hops each received packet traverses to reach the sink. This metric is used to evaluate the routing performance of each suite.

Latency is the time it passes between the time a packet is generated at a source node and the time it is received at the sink. This delay accounts for the queuing delay and the contention delay at the nodes as well as specific protocol operation overhead.

3.1 XLP Parameters

The parameters that affect the XLP operation are angle based routing, SNR threshold, $\sum_{Th}$, and duty cycle, δ. The effects of these parameters on the XLP performance in this section.

The end-to-end latency is shown, which reveals that increasing SNR threshold, ∑Th , improves the end-to-end latency performance up to a certain ∑Th value. ∑Th =10dB results in the lowest latency. It is also interesting to note that there is a suitable operating point for duty cycle δ considering end-to-end latency (δ~0.6) above this value, delay starts to increase because of the increase in receiver based contention. Since, for all above performance metrics, ∑Th =10dB results in the most efficient performance.

3.2 Comparative Evaluation

Evaluation is as follows:

Flooding. This configuration serves as the baseline for the other configurations. Each node broadcasts its packet and the nodes that are closer to the sink rebroadcast this packet until it reaches the sink. At the MAC layer, a CSMA-type broadcast mechanism is used. No retransmission mechanism is used. At the transport layer, packets are injected at a constant rate and no rate control is used. The results shown include the unique packets received at the sink.

[GEO]: Geographical Routing + CC-MAC + ESRT.

[PRR]: PRR-based Geographical Routing + CC-MAC + ESRT.

[PRR-SMAC]: PRR-based Geographical Routing + SMAC + ESRT.

[DD-RMST]: Directed Diffusion + RMST.

Accordingly, in GEO, PRR, and PRR-SMAC, each node broadcasts a beacon to inform its position and the remaining time to sleep. This beacon is sent at the beginning of each sleep frame when a node wakes up. Each neighbor that receives this beacon determines that the specific node will be active for the duration specified in the beacon. In GEO and PRR, the beacons are piggybacked if there is a packet in the queue. In PRR-SMAC, a pair wise cross layering is used and the routing beacons are sent with the SYNC packets. Similarly, SYNC packets are piggybacked if there is a packet in the queue.

3.2.1 Results

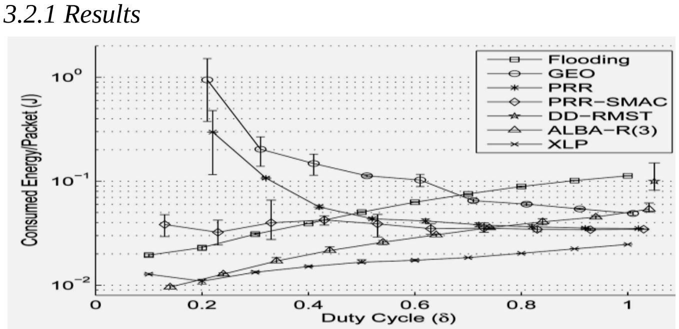

Fig. 4. Average energy consumption per packet versus duty cycle for different values of ∑Th.

The advantages of using a separate routing layer in the layered protocol suites, where the average hop count is shown. GEO, PRR, PRR-SMAC, and DD-RMST result in a fewer number of hops than XLP (for GEO and PRR performance, see [2]). This is due to the fact that the routing algorithms in these layered protocol suites aim to find the smallest number of hops. This result may beincorporated as a disadvantage of XLP when only the routing layer is taken into account. However, the overall performance of XLP reveals that maximizing the routing layer performance alone does not provide efficient communication in WSNs. In other words, while a smaller number of hops might be optimal in terms of routing efficiency, other effects such as link quality, contention level, congestion level, and overall energy consumption necessitate a cross-layer approach in route selection for overall efficiency.

3.2.2 Implementation Complexity

One of the major advantages of cross-layer design for communication protocols is the implementation efficiency. In traditional layered protocol architecture, each layer has clear boundaries. This layered structure leads to computation delays due to the sequential handling of a packet. For example, in TinyOS [9], [10], each layer has to wait for the lower layers to process the packet since a single buffer is used for a packet for all layers. XLP, however, blends the functionalities of traditional medium access, routing, and congestion control into a unified cross-layer communication module by considering physical layer and channel effects. Hence, these functionalities are performed as a whole and the overall protocol efficiency can be improved using XLP.

The extra space required by the communication stacks limits the available space to develop new applications for sensor networks. On the other hand, the careful use of code space and cross-layer implementation of communication functionalities in XLP provides a more efficient operation in WSNs. When coupled with the noticeably better communication performance, XLP becomes a successful candidate for communication protocols in WSNs.

In addition to the simulation performance, the implementation issues are also important for a complete comparison. As explained in Section 3, XLP does not require any tables or extra buffer space for routing and congestion control functionalities. The routing is performed based on receiver initiatives, which eliminates the need for a routing table at each node. The implementation of XLP is both simple and compact. On the other hand, in PRR-SMAC, the SMAC protocol maintains a schedule table for each of the one-hop neighbors to provide synchronized sleeping cycles. Similarly, in DD-RMST, at the routing layer, each node has to implement a reinforcement table for each source indicating the next hop in the reinforced path. In case a node is a source node, it also has to keep track of multiple neighbors which have a path to the sink for exploratory messages. At the transport layer, RMST requires a separate queue to cache data locally to support loss recovery at all hops. These requirements, due to either layered operation of the protocol stack or the internal protocol structure at each layer, place a burden on memory space for communication in sensor nodes. Compared to the layered protocol stacks, ALBA-R requires smaller code space because of the cross-layer MAC/ routing operation.

However, compared to XLP, ALBA-R necessitates large state information to be stored in each node because of the QPI and GPI scanning process.

IV. CONCLUSION

Efficient and authentic wireless communication is the most demandable area in network technology. So, for making rapid development in this sector, future generation of wireless network has more challenges for providing end-to-end , high-quality and reliable performance in multimedia communications. These conduct to cross layer design for wireless networks. The vehemence of these issues will be on cross layer protocol interactions and design of cross layer optimized techniques.

Initiative determination concept that allows many communication and networking functionalities be implemented in a single protocol. Accordingly, the cross-layer procotcol (XLP) is proposed to provide the functionalities of medium access, routing, and congestion control. Based on the initiative determination concept, XLP serves as a proof of concept and performs receiver-based contention, initiative-based forwarding, local congestion control, and distributed duty cycle operation to realize efficient and reliable communication in WSNs. Analytical performance evaluation and simulation experiment results show that XLP significantly improves the communication performance and outperforms the traditional layered protocol architectures in terms of both network performance and implementation complexity.The ultimate goal in the cross-layer design technique is to develop a single communication module that is responsible for the functionalities of each networking layer.

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