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Traffic Adaptive Priority Assignment Scheme for Congestion in IEEE 802.15.4 Networks

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***Abstract*—In this paper, we tackle the issue of exploiting the priority based packet assignments and transmissions in congested wireless sensor networks. Since the heavy traffic makes it difficult to provide QoS solutions, we propose a traffic adaptive priority assignment scheme (TAPA), which monitors the buffer length of each node to identify the congestion symptom and dynamically adjusts its backoff value and frame retransmission parameter according to predefined access categories (ACs). In addition, when TAPA detects congestion symptoms, it deliberately restrains from participating in the route discovery procedure by dropping RREQs and RREPs. We also conducted a performance evaluation via simulations and showed that TAPA provides a more efficient QoS solution than conventional IEEE 802.15.4 in terms of packet delivery ratio and end-to-end delay.**

Keywords—IEEE 802.15.4 Network; Congestion; Priority Assignment; MAC Protocol

I. INTRODUCTION

A Wireless Sensor Network (WSN) is one of the most rapidly growing technologies to access network resources easily, any time, anywhere, in a timely way. In WSNs, sensor nodes are scattered and their positions are not strictly predetermined. That is, the WSN is a self-configuring network of tiny nodes that is connected by wireless channels and it is applicable to various purposes such as remote healthcare, industrial monitoring, remote device control and etc. In particular, there are numerous potential opportunities for exploiting WSNs in a wide range of healthcare areas, such as emergency patient monitoring, personal health recording, and remote diagnosis. However, for the deployment of WSN based healthcare assistance systems, a number of unresolved problems remain. The most representative among these are as follows. Firstly, the devices with tiny sensors basically use a limited wireless channel that is significantly error prone compared with other wired network systems. Hence, this unreliable feature is extremely critical to process medical data. Second, the conventional MAC protocols such as SMAC [1], BMAC [2], IEEE 802.15.4 [3] do not define Quality of Service (QoS) policies and data differentiations for transmitting emergent medical packets. Third, as the demand for real time and multimedia data traffic grows, the occurrences of network congestion and related packet delay are inevitable over bandwidth limited WSNs. In such congestion situation, the conventional contention based backoff function for long term fairness is not suitable for QoS support because the existing Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) based MAC protocols do not provide differentiated channel accesses according to the packet priority. Furthermore, this congestion problem additionally leads to severe performance degradations such as buffer overflows, link failure, network partitions. Hence, this implies that a WSN based healthcare system should provide not only priority assignment based packet transmissions but also robust channel access in congested environments.

In order to deal with communication reliability and efficiency at the MAC layer, a lot of WSN protocols also have been proposed. For example, OPAM [4] is one of the most representative QoS provision schemes for medical grade data. It provides dynamical scheduling services for different types of packets by monitoring the queue latency of each node. However, it neglects to consider the dynamic backoff mechanism which takes more time to access the channel than queuing delay. PRIMA [5] is another priority queue based MAC protocol which combines both CSMA and Time Division Multiple Access (TDMA) operations for efficient QoS scheduling. HMAC [6] is also a hybrid approach based on combined operations for CSMA and TDMA. Authors in [7] propose a dynamic Contention Window (CW) tuning protocol which satisfies application specific QoS requirements. However, it does not introduce detailed access categories or QoS levels for medical data. And both [5] and [6] require strict time synchronization for dealing with TDMA based operations, which is not appropriate for mitigating the effect of topology changes.

In this paper, we propose a new scheme, called TAPA (Traffic Adaptive Priority Assignment), to provide medical grade QoS packet transmission and enhance the channel reliability by dynamically tuning the backoff value and the number of retransmission trials at the MAC layer especially in congested WSNs. When the heavy traffic is provided, the high priority packets are promptly transmitted by reducing the backoff counter, and they also have more retransmission opportunities for high reliability. On the other hand, the packets with low priority yield their channel acquisitions by setting high backoff values in order to guarantee medical grade QoS support over resource limited WSNs. In addition, TAPA also provides a dedicate path for emergent packets by dropping RREQs and RREPs from low priority sources especially when the network is judged to be congested.

The rest of this paper is organized as follows. In section II, we describes the proposed protocol in detail and Section III presents the performance evaluation of the proposed protocol. Finally, concluding remarks are given in section IV.

II. Proposed Scheme

In this section, we introduce the detailed operations of the proposed scheme, named TAPA, to provide differentiated packet transmission services over WSNs. Since TAPA mainly focuses on resource limited WSNs, the target network is assumed as follows. First, the network adopts the IEEE 802.15.4 based channel contention scheme for wireless medium access without TDMA based channel synchronization. Although TDMA is efficient for QoS support by using the Contention Free Period (CFP) mechanism, it is still difficult to cope with the multi-hop network and topology changes. Second, all sensor nodes continuously transmit their sensing data to a small number of sink nodes, which may result in network congestion in bottleneck areas. Finally, each sensor node initially knows its data priority by referring to the application level, after which the node allows TAPA to perform priority based packet transmissions.

Since the main goal of the proposed scheme is to provide a priority based packet transmission, TAPA defines the packet priority according to their importance of the application. For this, TAPA defines four different Access Categories (ACs) which are consisted of medical grade (AC3), surveillance grade (AC2), best effort grade (AC1) and yield grade (AC0). These different ACs are inserted into separated scheduling queues in the node as shown in figure 1.

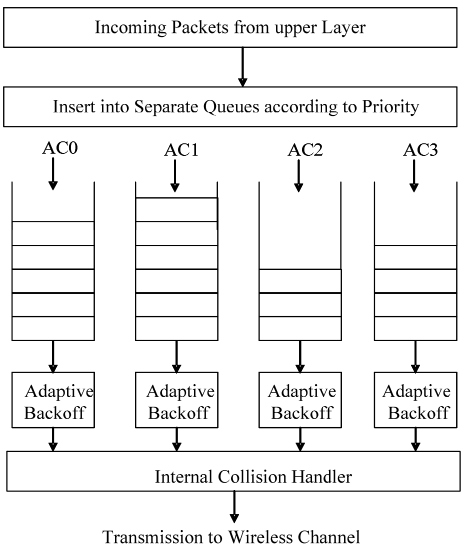

Fig. 1. Separated queues for different access categories in a node

After the packet priority of the sensor node is determined according to ACs, the node starts to transmit data frames by using the TAPA operations which are described in table 1. The first operation of TAPA is to monitor the interface queue length of each node in order to identify whether or not the network is congested. To do this, TAPA defines B_{CUR} and B_{TH} which denote the current buffer length and a buffer threshold value of the node, respectively. If B_{CUR} is larger than B_{TH}, the current state of the node is believed to be eventually congested. That is, the node is considered that it cannot efficiently handle prioritized packets. In particular, the backoff time of IEEE 802.15.4 is calculated by a random function (2^{BE} -1) and the default Minimum BE (MinBE) and Maximum BE (MaxBE) are 3 and 5, respectively. Thus, the conventional backoff range cannot properly tackle emergent packets especially when the network is congested. In order to resolve this problem, TAPA dynamically adjusts the random backoff time by configuring adaptive MaxBE (AMaxBE) and adaptive MinBE (AMinBE). In case of medical grade data (AC3), AMaxBE is determined by the expression D_{MAX} - B_{EX}, where D_{MAX} is a default MaxBE value of IEEE 802.15.4 and B_{EX} is the buffer excess factor which is calculated by equation (1).

$$B_{EX} = \left\lfloor \frac{B_{CUR} - B_{TH}}{\text{The length of buffer}} \times 10 \right\rfloor \tag{1}$$

Similarly, AMinBE is calculated by subtracting B_{EX} from D_{MIN}, where D_{MIN} is a default MinBE value of IEEE 802.15.4. These operations lead to exponential reduction of the backoff delay in order to transmit medical data packet faster than the other packets. In addition, TAPA gives more retransmission opportunities for the reliability by increasing AMaxRetry which denotes the maximum number of retransmission attempts allowed after link failures at the MAC layer. And it is calculated by adding B_{EX} to D_{RETRY}, where D_{RETRY} is the default frame retransmission value of IEEE 802.15.4.

Table 1. Operation of TAPA

Priority based Packet Assignments for ACs		
Type	***AC***	***CW Tuning***
Medical grade	3	If $B_{CUR} > B_{TH}$ then AMaxBE = D_{MAX} - B_{EX} AMinBE = D_{MIN} - B_{EX} AMaxRetry = D_{RETRY} + B_{EX} Delay for Random ($2^{[AMinBE, AMaxBE]}$ - 1)
Surveillance grade	2	If $B_{CUR} > B_{TH}$ then AMaxBE = D_{MAX} AMinBE = D_{MIN} Delay for Default (Backoff - B_{EX})
BestEffort grade	1	Delay for Default Backoff (IEEE 802.15.4)
Yield grade	0	If $B_{CUR} > B_{TH}$ then AMaxBE = D_{MAX} + B_{EX} AMinBE = D_{MIN} + B_{EX} AMaxRetry = D_{RETRY} - B_{EX} Delay for Random ($2^{[AMinBE, AMaxBE]}$ - 1)

The surveillance grade (AC2) is used for the second most emergent data such as security and control purposes which require still faster transmissions than best effort data. In AC2, although the node has default MaxBE and MinBE for more restrained access than AC3, it performs a random backoff function by subtracting B_{EX} from the default backoff value. For typical best effort packets, TAPA uses AC1 which performs the default backoff function of IEEE 802.15.4. Finally, AC0 represents a yield grade packet that yields its channel access opportunity to AC3 traffic in order to guarantee reliable and prompt transmissions for medical data. To do this, when AC0 overhears any packet transmissions of AC3, it takes a relatively larger backoff value than AC3. Similarly, AC0 has less frame retransmission opportunities than AC3 in order to provide AC3 with more reliability. Note that these yield operations are considered as resource compensation since the immoderate BE tuning with small backoff values for AC3 may lead to significant packet collisions and make the congestion worse.

Although the proposed adaptive backoff scheme provides efficient packet differentiation services, it does not guarantee reliable routing for emergent data at the network layer. Since conventional on-demand routing protocols (i.e. AODV [7] and DSR [8]) merely establish a route with the minimum number of hops, the traffic is easily concentrated on a certain intermediate node especially when the node responds with Route Response (RREP) by using its route cache information. To mitigate this problem, TAPA allows the node that relays AC3 packets to drop new RREQs or RREPs if it detects that B_{CUR} is larger than B_{TH}. Consequently, this suppression provides not only congestion avoidance but also reliable transmissions for emergent packets.

III. PERFORMANCE EVALUATION

A. Simulation Environments

To verify the performance of the proposed scheme, we conducted experiments via NS2 simulator [9] and compared with conventional IEEE 802.15.4. For the routing protocol, we used AODV and the experiments lasted 900 seconds. There are 100 sensor nodes including a sink node, which are assumed to be randomly placed in an 80m by 80m network topology. All sensor node except the sink node move randomly at given speed with 5km/h which reflects the typical walking speed of people. The transmission range and interference range of each node is set to 9m and 18m, respectively. We used 30 data connections (AC3 flows: 5, AC2 flows: 10, AC1 flows: 15) between source and the sink node. The maximum buffer size of each node's interface is set to 50 and B_{TH} is set to 25 which is 50% of buffer size. Each source node generates constant bit rate (CBR) traffic with packet size of 50 bytes. The reason why we adopt CBR is that TCP may invoke its own congestion control at the transport layer, which is difficult to observe the network congestion and the performance of TAPA operations. In addition, we configured the node scheduling with 100% duty cycle to represent continuous packet transmissions which can create a congestion situation. In order to represent dynamic traffic load, we used 8 different packet arrival time from 0.1 to 0.8 seconds.

B. Simulation Results

After configuring the simulation environments, we measured packet delivery ratio and end-to-end delay which are the average number of packets successfully received by the sink node over the number of packets generated by source nodes and the average time that elapses from the time a packet is transmitted by the source node to when it is received by the sink node, respectively.

Figure 2 shows the delivery ratios of IEEE 802.15.4 and TAPA as a function of the traffic interval. Since TAPA supports 4 different ACs, each AC is separately measured to identify its effects. When the network is heavily congested (e.g. traffic interval is less than 0.5), the delivery ratios of emergent packets (e.g. AC2 and AC3) show better performance than the other flows including IEEE 802.15.4 because emergent data has more transmission opportunities and it is routed via a dedicated path.

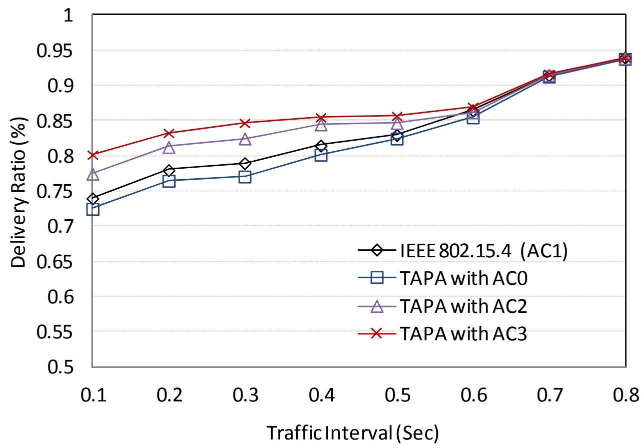

Fig. 2. Packet delivery ratio

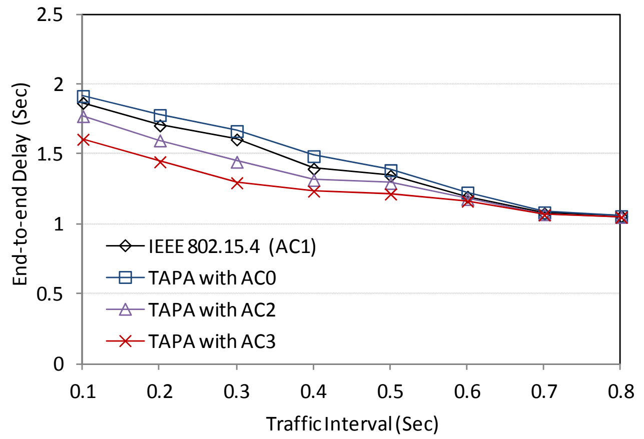

Fig. 3. End-to-end delay

Figure 3 describes the end-to-end delay performance comparison of IEEE 802.15.4 (AC1) and TAPA flows (AC0, AC2, and AC3). Similarly with the delivery ratio, TAPA with AC3 and AC2 packets are delivered more promptly than other data such as AC1 and AC0. This is because the emergent data can easily win the channel competition by configuring smaller backoff values than the best effort and yield grade data. Although the yield data (AC0) shows poor performance with respect to both end-to-end delay and delivery ratio compared to IEEE 802.15.4, the performance gap is smaller than the gap between emergent traffic and IEEE 802.15.4. This is because TAPA efficiently distributes the data traffics by refraining from participating in the route discovery procedure, which prevents buffer overflows and unnecessary route failures.

IV. CONCLUSION

In this paper, we present a traffic adaptive priority assignment scheme called TAPA for congested WSNs. Firstly in order to define priority levels for each data packet, TAPA newly suggests four different access categories (ACs) consisted of medical grade, surveillance grade, best-effort grade and yield grade. The medical and surveillance data is considered as emergent traffic and is configured with high priority channel access attempts by setting less backoff values and large frame retransmission values according to the degree of congestion status. On the other hands, the yield traffic has relatively less transmission opportunities in order to provide emergent traffic with more reliable transmissions. The congestion status is monitored by the buffer threshold values of each node. In addition, if the network is considered to be congested and the node relays the most emergent packets, the node selectively drops RREQs and RREPs in order to provide emergent traffic with a dedicated path. Through the simulation study, we observed that TAPA shows a good performance in terms of packet delivery ratio and end-to-end delay when the network is heavily loaded.

In future works, we plan to develop a more reliable routing protocol for multi-hop based WSNs to cope with dynamic environments. In addition, we will study optimized cross-layer operations for improving QoS solutions.

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