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Dynamic Multi-Channel Allocation Mechanism for Wireless Multimedia Sensor Networks

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***Abstract*—In the Wireless Multimedia Sensor Networks (WMSNs) field, real-time multimedia flow increases the probability of collision and congestion in sensor network which degrade the performance of Quality of Service (QoS). How to meet the high QoS requirement of WMSNs applications under the condition of energy constraint is a crucial issue. In this paper, we propose a predicted available bandwidth estimation based dynamic multi-channel allocation mechanism, non-overlapping channels is dynamically deployed according to the channel allocated admission algorithm for the different application loads. Further, energy consumption model called energy per successfully transmitted bits (ESTB) based on CSMA-CA procedure of IEEE 802.15.4 standard is introduced to offer more objective analysis on the estimation of energy consumption. Simulation result shows the dynamic multi-channel allocation approach perform better than benchmark on the metrics of reliability and latency, achieves the trade-off between energy efficiency and QoS requirement.**

***Index Terms*—IEEE 802.15.4; WMSN; Multi-channel; QoS; Bandwidth Estimation**

I. INTRODUCTION

In the last two decades, along with the proliferation in Micro-Electro-Mechanical Systems (MEMS) technology which has motivated the development of smart sensors [1], WSN field witnessed explosive development and attracted broad attention in the world. A typical WSN is a collection of wireless nodes with multifunctional sensor collaborate together to monitor assigned area to accomplish a sensing task for dynamically changing environment. Tracking (e.g. enemy tracking, habitat tracking, etc.) and monitoring (e.g. environmental monitoring, industrial processes automation, etc.) are two major application fields in sensor network. However, with the development of Wireless Multimedia Sensor Network (WMSN) which is composed by embedded cameras and microphones besides scalar sensors, real-time multimedia applications require high level Quality of Service(QoS) guarantee in high data delivery rate flows. Increasing interference combined with the overheads of MAC protocol limit the available bandwidth in WMSN. These overheads can result in congestion which degrades the performance and reliability of WMSNs.

In this paper, we will propose a dynamic multi-channel allocation mechanism for IEEE 802.15.4-based networks. On the one hand, the bandwidth limitation of single channel protocol results in the performance degradation in the case of saturate real-time multimedia stream application of WMSNs. On the other hand, in the existing multi-channel based protocol designed for WMSNs, stationary non-interference transmission channels are deployed in sensor network with various structures. However, due to the uncertainty of sensor network, various application schedules and different density of sensor tasks generate instantaneous floating data flows. Constant or static channels deployment causes additional energy overhead and channel interferences. For the dynamic multi channel allocation mechanism, non-overlapping channels are dynamically allocated according to the instantaneous performance of QoS. Bandwidth is a crucial resource in WMSNs, has a tight relevance with performance of QoS and energy consumption. Limited throughput along with cross-layer overhead and interference give rise to congestion and collision which increase end-to-end latency and packet error rate correspondingly. The degradation of performance accompanies Medium Access Control (MAC) protocol process further impact on the available bandwidth. Thus, residual available bandwidth is selected as metric to evaluate the global performance and considered as the trigger mechanism in our multi-channel allocation algorithm. Furthermore, derived from the Markov model of CSMA-CA protocol on MAC layer and channel error module on PHY layer [2], a energy consumption model called energy per successfully transmitted bits (ESTB) is presented in this paper to evaluate energy consumption in case of saturate network condition with more objective interpretation. The energy consumption module considers comprehensive reliability of cross-layer protocol and energy overhead of backoff procedure to evaluate the expectation of energy consumption for transmitting a bit successfully.

The remainder of this paper is organized as follows. Section II represents related work that inspire our work. In section III, our dynamic multi-channel allocation mechanism is proposed and discussed in detail. Section IV illustrates simulation scenario and performace evaluation result. Finally this paper is concluded in Section V.

II. RELATED WORK

Adaptive Access Parameters Tuning (ADAPT) mechanism [3] is an adaptive and cross-layer framework which involves an energy-aware adaptation module that captures the reliability requirement of applications, and autonomously configures MAC layer based on the network topology and the traffic conditions in order to minimize power consumption.

Reference [4], proposed a passive bandwidth estimation techniques (ABE) based on IEEE 802.11 ad hoc networks. The bandwidth estimation model combined carrier sense capacity with collision and back-off prediction techniques. In the flow admission control mechanism, ABE was integrated into AODV that exchange their available bandwidth information with neighboring nodes through HELLO messages. Source node broadcasts the information of bandwidth requirement which is integrated into route request packet (RREQ) to neighbors and make the comparison with available bandwidth estimation in order to make the admission control decision.

Multi-channel MAC protocol (MC-LMAC) [5] has been proposed with the objective to impove throughput of network by transmitting with multiple frequency channels. MC-LMAC integrated multi-channel allocation method into TDMA scheme, every node could select unique time slot periodically to transmit packet in independent time slot on a particular channel without conflict with other link in the same time slot and same frequency channel.

BandEst [6] is a measurement available bandwidth estimation based flow admission control algorithm for wireless multimedia networks. As a enhancement of ABE method [4], the proactive bandwidth estimation considers the additional back-off overhead due to future data load on the IEEE 802.15.4 based CSMA-CA MAC layer. Inra-flow contention measurement, additional MAC layer overhead, contention on non-relaying nodes and concurrent admission requests are taken into account in BandEst's flow admission control algorithm.

The prototype of Multi-channel IEEE-802.15.4 packet capture established on software defined radio was implemented in [7]. This design was for 5 consecutive channels of the 16 channels located in the 2.4 GHz band, GNU Radio was used to separate the sampling window into different channels and process demodulatation in parallel procedure.

In [8], the authors provide mathematical model of energy consumption for successfully received bit over a particular distance and channel noise model that include AWGN channels and block Rayleigh fading channels. Besides, the analytical framework was proposed for numerical optimization of PHY layer parameters which contains modulation scheme, transmit power, and hop distance in order to arrive at the minimum transmission energy consumption.

III. DYNAMIC MULTI-CHANNEL ALLOCATION MECHANISM

For deploying multiple channels dynamically, currently residual available bandwidth ratio is considered as the metric in order to indicate the global performance of node, which is derived from proactive passive bandwidth estimation approach [9]. Moreover, considering the predicted backoff and contention window overhead on MAC layer and additional wastage due to PHY channel constraints, the admission control algorithm of channel allocation mechanism determines the optimization numbers of active channel for the next communication period. Based on cross-layer IEEE 802.15.4 analysis model, the channel allocated admission algorithm is integrated into this framework to evaluate the discrepancy of performance on QoS and energy efficiency.

A. Bandwidth Estimation Module

The residual available bandwidth estimation module gathers recently parameters of overhead information from MAC layer and physical layer, it retrieves the total actual CSMA-CA MAC layer overhead information and the summation of data generation rate of physical layer. Then the comparision between the current bandwidth overhead calculation and the current maximum channel rate will result in the estimation of residual available bandwidth, as shown in equation 1.

$$\omega_t = CR_t^{max} - \sum_{i=1}^{\kappa} \mu_t^i \Big/ \kappa - \sum_{i=1}^{\kappa} \varphi_t^i \Big/ \kappa \tag{1}$$

Where, ω_t is the residual available bandwidth in bits per second (bps) of the t-th state, CR_t^{max} indicates the maximum channel rate of the t-th state, κ represents the current size of averaging window. μ_t^i represents the instant application data generation rate on physical layer in i-th contention window interval, φ_t^i represents the CSMA-CA overhead on MAC layer in i-th contention window interval, the estimation module of additional bandwidth overhead due to collision and backoff procedure is derived by [4]. In order to avoid the estimation available bandwidth value too sensitive to sudden variation of wireless sensor network, exponential moving average is applied to smooth the estimation value of residual available bandwidth as follows:

$$\overline{\omega}_{t+1} = \alpha\omega_t + (1-\alpha)\overline{\omega}_t \tag{2}$$

where $\overline{\omega}_{t+1}$ indicates the available bandwidth of the $t+1$-th estimation state, $\alpha \in [0,1]$ is smoothing factor. Considering the random nature of wireless sensor networks, α is assigned to 0.7 in order to track the variation trend based on the history available bandwidth value.

B. Channel Allocation Control

The procedure of channel allocated admission control is illustrated in figure 1. The residual bandwidth estimation module collects the current t-th state information from PHY and MAC layer, available bandwidth ratio is exploited and calculated via the comparison between estimation value for next $t+1$-th period state and maximum bandwidth for current period state. Simultaneously, channel allocated admission control module retrieves various performance information (e.x. packet error rate, delay, energy consumption) from MAC layer, then two tunable threshold value could be defined in order to trigger allocation algorithm. If the result of available bandwidth ratio exceeded the predefined threshold value of ω^{high} or ω^{low}, optimization of channel numbers CN_{t+1} for next period state is executed. The maximum possible orthogonal channels are pre-defined according to sensor network topology and size. The details of the allocation admission control procedure is illustrated in Algorithm 1.

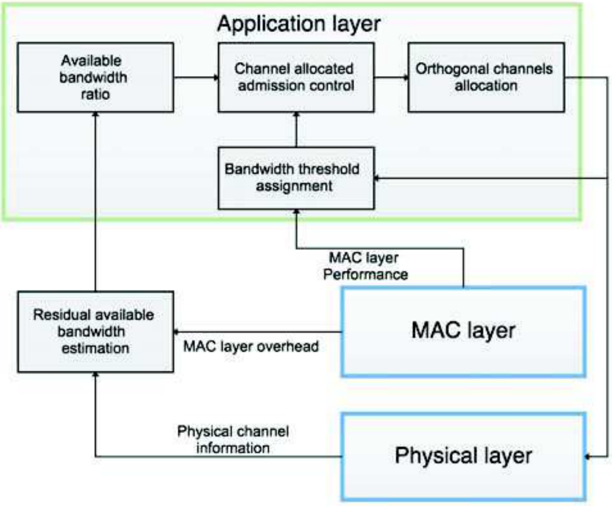

Fig. 1: Dynamic Channel Allocation Structure

C. Cross-layer IEEE 802.15.4 Model

The cross-layer analytical IEEE 802.15.4 model is introduced to evaluate the performance of multi-Channel bandwidth allocation framework. For the MAC layer part, we adapted the generalized analytical model proposed by [10] which is based on CSMA-CA exponential backoff procedure model in Markov chain taking into account retry limitation, acknowledgements and traffic. The PHY layer module is derived from [2] which considers physical channel parameters and fuse the impact of physical layer errors with MAC layer in order to obtain more precise output estimations.

In the Markov Chain model, three channel access probabilities τ, α and β are defined. They denote the probability that a node attempts a first carrier sensing in a randomly time slot, the probability of channel busy in first clear channel assessment $CCA1$ and the probability of channel busy in $CCA2$ respectively. The system model is distributed as follow:

$$\tau = (1 - P_{idle})\left(\frac{1 - x^{m+1}}{1 - x}\right)\left(\frac{1 - y^{n+1}}{1 - y}\right) b_{0,0,0} \tag{3}$$

$$\alpha = (1 - (1 - \tau)^{N-1})(1 - \alpha)(1 - \beta)\left(L + L_{ACK}\frac{N\tau(1 - \tau)^{N-1}}{1 - (1 - \tau)^{N}}\right) \tag{4}$$

$$\beta = \frac{1 - (1 - \tau)^{N-1} + N\tau(1 - \tau)^{N-1}}{2 - (1 - \tau)^{N} + N\tau(1 - \tau)^{N-1}} \tag{5}$$

$$x = \alpha + (1 - \alpha)\beta \tag{6}$$

$$y = (1 - (1 - P_c)(1 - P_{loss}))(1 - x^{m+1}) \tag{7}$$

Algorithm 1: CHANNELALLOCATEDADMISSIONCONTROL

```
Input: $CN_t$: Current channel numbers;
       $CR_t^{max}$: Current maximum bandwidth;
       $\overline{\omega}_t$: Available bandwidth estimation of current
       state $s_t$;
       $\varphi_t$,$\mu_t$: Current information from MAC layer and
       physical layer
Output: $\overline{\omega}_{t+1}$: Estimation of available bandwidth in
        next state $s_{t+1}$;
        $CN_{t+1}$: Estimation of channel numbers in
        next state $s_{t+1}$
update $\omega^{low}$, $\omega^{high}$
Estimate available bandwidth $\omega_t$
$\overline{\omega}_{t+1} \leftarrow \alpha\omega_t + (1 - \alpha)\overline{\omega}_t$
if $\overline{\omega}_{t+1} \leq \omega^{low} CR_t^{max}$ then        // Saturated State
    if $CN_t < CN_{max}$ then
        $CN_{t+1} \leftarrow CN_t + 1$
    else
        $CN_{t+1} \leftarrow CN_{max}$
    end
end
if $\overline{\omega}_{t+1} \geq \omega^{high} CR_t^{max}$ then    // Unsaturated State
    if $CN_t > CN_{min}$ then
        $CN_{t+1} \leftarrow CN_t - 1$
    else
        $CN_{t+1} \leftarrow CN_{min}$
    end
end
if $\overline{\omega}_{t+1} > \omega^{low} CR_t^{max}$ and $\overline{\omega}_{t+1} < \omega^{high} CR_t^{max}$ then
    $CN_{t+1} \leftarrow CN_t$                          // Steady State
end
return $\overline{\omega}_{t+1}$, $CN_{t+1}$
update $CN_{min}$, $CN_{max}$, $s_{t+1}$
```

where, m and n represent the maximum value of $macMaxCSMABackoffs$ and $macMaxFrameRetries$ in CSMA-CA, respectively. x indicates the probability of channel congestion in $CCA1$ or $CCA2$, y indicates the probability of failed trasmission due to the probability of collision P_c that several nodes transmit in the same time slot or the probability of message loss P_{loss} due to physical channel constraints. L and L_{ACK} represent the length of data frame and acknowledgements in slots, respectively. N is the number of neighbouring stations. Based on the channel access probability of each state in CSMA protocol procedure, the QoS and energy consumption of system can be described respectively. R is defined as the reliability of successfully delivery probability, as shown in follows:

$$R = (1 - P_{blk})(1 - P_{caf} - P_{rtx}) \tag{8}$$

$$P_{caf} = \frac{x^{m+1}(1 - y^{n+1})}{1 - y} \tag{9}$$

$$P_{rtx} = y^{n+1} \tag{10}$$

where, P_{caf} indicates the probability of channel access failure due to maximum times of back-off procedure. P_{rtx} represents the probability of transmissions failure due to the maximum times of retransmission attempts. P_{blk} is the probability that no available buffer remain.

The average delay is considered as the elapsed time interval for every successfully transmission divided by reliability, as illustrated in equation 11.

$$T_{delay} = \frac{\sum_{i=0}^{n} (1-y) y^{i} (T_s + i T_c + (i+1) T_{backoff})}{(1-P_{blk})(1-P_{caf}-P_{rtx})} \tag{11}$$

where, T_s is the time delay for a successful transmission access, T_c is the time delay because of collision in CCA, $T_{backoff}$ represents the average time delay for a successful CCA procedure.

For the existing energy consumption analysis in IEEE 802.15.4 model, percentage of each states in every transceiver time slot is computed, then multiply them by the power consumption of each state respectively, the summation is the approximate estimation of energy consumption in each time slot. In order to achieve more objective energy analysis which approximate to measurement value, a energy consumption model is proposed which consider the energy consumption in different states of backoff mechanism in MAC layer. We get inspired from [8], which derive the model for the energy per successfully received bit (ESTB) for a given transmitter/receiver structure and packet structures. As shown in figure 2, energy consumption is distinguished based on the backoff procedure for IEEE 802.15.4 CSMA-CA protocol. E_{CCA} represents the energy consumption of performing a CCA in PHY layer, CCA is indispensable procedure before the attempt to transmit package which consume larger energy than energy consumption E_{tx} in transmission [11]. $E_{backoff}$ represents the energy consumption of performing a complete procedure of backoff mechanism, depicted in equation 12. Explicit communication, it can be treated as the expectation that is derived from E_{CCA} with perform coefficient. The perform coefficient is determined by the contention window size and $macMaxCSMABackoffs$. Thus, the expectation of energy consumption can be estimated separately based on respective state of CSMA-CA mechanism (equation 13-15). E_R represents the expectation of energy consumption to transmit a package successfully. E_{caf} represents the expectation of energy wastage in the procedure of channel access failure due to the limitation of $macMaxCSMABackoffs$. E_{rtx} represents the wasted energy of transmissions failure due to the maximum number of retransmission attempts.

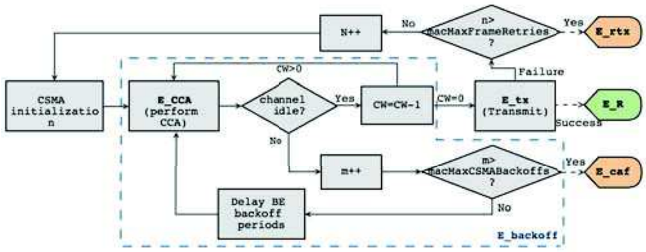

Fig. 2: Analysis of Energy Consumption for CSMA-CA protocol

$$E_{backoff} = \sum_{i=0}^{m} (\alpha - (1-\alpha)\beta)^{i} \cdot \left(2 + \frac{\alpha + 2(1-\alpha)\beta}{\alpha + (1-\alpha)\beta} i\right) E_{CCA} \tag{12}$$

$$E_R = \sum_{j=0}^{n} y^{j} (j+1)(E_{backoff} + E_{tx}) \tag{13}$$

$$E_{caf} = \sum_{j=1}^{n} y^{j} j (E_{backoff} + E_{tx}) + \frac{\alpha + 2(1-\alpha)\beta}{\alpha + (1-\alpha)\beta} (m+1) E_{CCA} \tag{14}$$

$$E_{rtx} = (n+1)(E_{backoff} + E_{tx}) \tag{15}$$

$$ESTB = \frac{R \cdot E_R + P_{caf} E_{caf} + P_{rtx} E_{rtx} + P_{idle} E_{idle}}{R \cdot \lambda \cdot L_{APP}} \tag{16}$$

By considering all the valuable energy consumption and energy wastage in every state of the IEEE 802.15.4 model, $ESTB$ is estimated in equation 16. λ is the data generate rate per node. The energy consumption of the cross-layer IEEE 802.15.4 model is defined as the summation of energy overhead expectation in each state of system divided by the instantaneous reliable throughput.

IV. SIMULATION

We evaluated the performance of dynamic multi-channel allocation mechanism through the simulation by MATLAB r2014. The WSN is considered 5 to 20 sensor nodes in different simulation scheme, every node is defined as variable channels from default single channel to multi channels which is up to maximum 4 orthogonal channels. The size of application frame payload is 121 $bytes$, the size of overhead frame is set in 6 $bytes$. For the elementary energy consumption value in WSN, measurement value [12] is used for estimating the power consumption in each state of simulation, as listed in Table I.

TABLE I: Simulation Parameters

Parameter	Value	Parameter	Value
Node numbers	5-20	$L_{overhead}$	6 $bytes$
macMinBE	3	$L_{application}$	121 $bytes$
macMaxBE	5	E_{tx}	30 mW
macMaxCSMABackoffs	4	E_{rx}	40 mW
macMaxFrameRetries	3	E_{CCA}	40 mW
MinChannelNumbers	1	E_{idle}	0.8 mW
MaxChannelNumbers	4		

For the fundamental simulation scenario in our performance analysis, we consider that the application load for each node evolves in 80 simulation state periods. The simulation scenario is divided into two segments. Firstly, application load increases linearly untill it arrives at the peak of 8$kbps$ each node, then application loads decrease with Symmetrical trend until idle network condition, as indicated in Figure 3. The performance QoS and energy efficiency will be evaluated and analyzed based on different metrics separately.

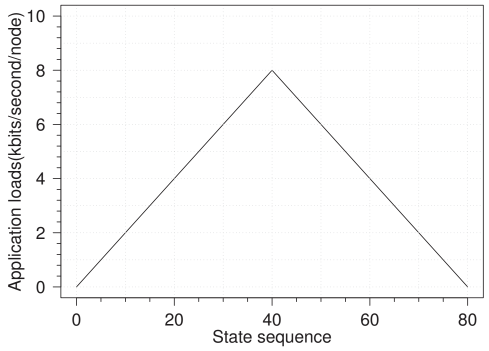

Fig. 3: Simulation Scenario

A. Quality of Service

In the first part, two performance metrics $Reliability$ and $Latency$ is considered in order to indicate the data accuracy and average elapsed time in network. 10 sensor nodes was considered in single-hop star network, packet loss rate P_{loss} due to physical channel constraints was set to 20% as a stationary condition. For the performance evaluation of dynamic multi-channel allocation algorithm, single channel with default parameter (SC_DP) is evaluated as benchmark scheme with default performance of CSMA-CA protocol for comparison propose. multi-channel dynamic bandwidth with tunable threshold (DMC_TP) indicates the performance values based on channel allocation algorithm with the tunable threshold parameter ω^{low} and ω^{high}. Here, we simplify consider the bandwidth threshold parameters as three pairs of stationary values that evaluated in DMC_TP for the analysis of performance dissimilarity: DMC_TP1 with parameter ω^{low}=0.1, ω^{high}=0.7; DMC_TP2 with parameter ω^{low}=0.2, ω^{high}=0.7; DMC_TP3 with parameter ω^{low}=0.3, ω^{high}=0.8.

The performance as a function of reliability is shown in Figure 4, the results confirm the previous presumption. Along with the increase of application load, the system global reliability of SC_DP has a conspicuous degradation due to the increasing possibility of retransmissions, back-off mechanism failure, collision and channel error. Increasing flow accompanied the additional bandwidth overhead due to MAY layer procedure cause the result of limited available bandwidth. Depicted from Figure 4, the performance of DMC_TP indicate a improvement in the range of saturate application flow condition. If the estimation ratio between proactive available bandwidth and current maximum bandwidth is in excess of the threshold value ω^{low} or ω^{high}, the channel allocated algorithm will be triggered and executed. Different threshold parameters has different susceptibility of trigger, DMC_TP3 performs the best in reliability compared to DMC_TP1 and DMC_TP2. Figure 5 indicates the performance of average latency in different schemes. Without the consideration of transport delay on PHY layer, only elapsed delay due to CSMA-CA procedure is calculated in this figure. Saturate application flow causes congestion on MAC layer processing, the retransmissions will trouble the delay time, higher possibility of CCA failure also increase the additional elapsed time overhead on clear channel assessment. Obviously, DMC_TP3 achieves the lowest latency value irrespective of the fluctuating application load.

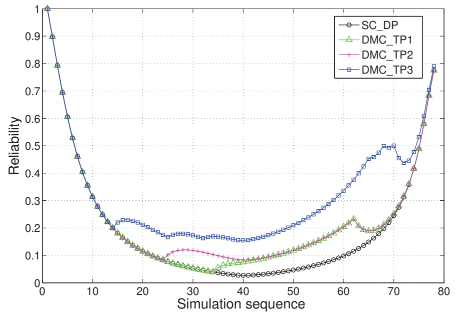

Fig. 4: Instant reliability with different parameters

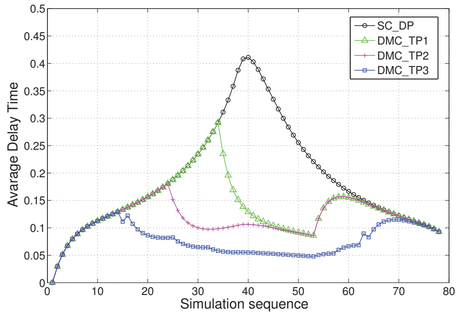

Fig. 5: Instant latency with different parameters

B. Energy Consumption

In the second part, the energy consumption per successfully transmitted bit (ESTB) is investigated to indicate the performance metric of energy efficiency and conversion efficiency from total energy consumption to actual data throughput in network. DMC_TP1 and DMC_TP3 are evaluated in the dynamic condition of packet loss rate P_{loss} in the constraint of physical channel for more precisely energy consumption evaluation result. Firstly, the performance result of instant ESTB value in 10 nodes network is shown in Figure 6. DMC_TP1 outperforms the result of SC_DP for the energy conversion efficiency in the saturate application load range. However, the ESTB result of DMC_TP3 does not converge to the value of SC_DP in the second part of the simulation sequences, stationary threshold value for channel allocated admission control hardly meet the

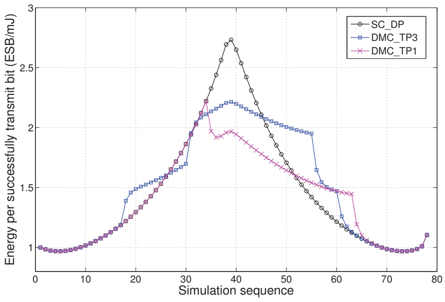

Fig. 6: Instant ESTB with different parameters

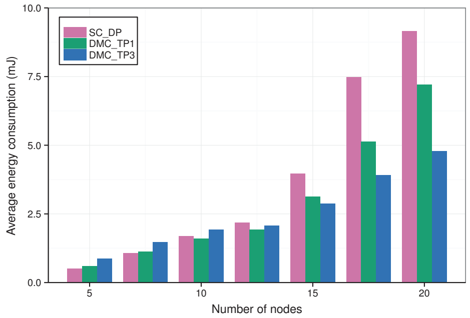

Fig. 7: Average ESTB of different sensor nodes

requirement of QoS and energy efficiency simultaneously. Secondly, the impact of the number of nodes on the performance of energy consumption is evaluated, as shown in Figure 7. Average ESTB value is calculated which depend on corresponding single-hop network sizes from 5 sensor nodes to 20 sensor nodes, simulation follows the same fundamental scenario (Figure 3) for different number of nodes. From the results we can see that DMC_TP consumes more energy compared with benchmark result in the case of senor nodes number is less than 10. Because of the small size of nodes number, the probability of collision and congestion between sensor nodes is limited in high application loads, the performance improvement of DMC_TP is inconspicuous compare to the excess energy consumption due to multi-channel mechanism. On the other hand, along with the growth of nodes number, the average energy consumption of benchmark increases dramatically. Because the greater number of nodes results in the increasing congestion and collision probability, the probability of failure CCA procedure in constant contention window size increases as well. The wasted energy consumption due to failure CCA and retransmissions procedure in CSMA-CA increases the average ESTB value. The average energy consumption of DMC_TP1 is lower but also has a increase trend similar to SC_DP when the number of nodes is above 12. DMC_TP3 has a linear increasing trend, outperforms others on the performances of average energy consumption when the number of nodes is above 15. In low number of nodes network, dynamic multi-channel allocation approach with lower sensitive trigger threshold value consumes lower average ESTB than the mechanism with high sensitive trigger threshold. For the high number of nodes network, dynamic multi-channel allocation mechanism with high sensitive trigger threshold consumes lowest average ESTB.

V. CONCLUSION

In this paper, based on the global performace indication of predicted available bandwidth estimation model, we have proposed a dynamic multi-channel allocation framework for adaptive reliable and energy efficient communication in IEEE 802.15.4-based wireless multimedia sensor network. The simulation result verifies that the available bandwidth-based dynamic multi-channel allocatation mechanism realizes the trade-off between energy efficiency and dynamic QoS requirement. However, single system decision-making is difficult to guarantee the overall performance based on QoS and energy management of WMSNs. In the future work, more intelligent system decision-making approach for dynamic and adaptive bandwidth threshold value will be integrated in the channel allocation mechanism.

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