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DESIGN, CHALLENGES AND FUTURE RESEARCH ASPECTS OF MAC PROTOCOLS FOR WIRELESS SENSOR NETWORKS

Pardeep Kumar*, Akhtar H. Jalbani**, M. Ibrahim Channa***, Anees A. Soomro****, Iftikhar A. Koondhar*****

ABSTRACT

The most substantial challenge facing Wireless Sensor Networks (WSNs) is the requirement of significant reductions in energy consumption of sensor nodes. Size and cost limitations result in a very limited on-board power capacity and the dense, remote and inaccessible deployment of sensor nodes prevents recharging their batteries, making energy a scarce resource for WSNs. A medium access control (MAC) protocol for WSNs, apart from other responsibilities, can substantially conserve the energy of a node by controlling the functionality of radio, which is the major energy consuming component of the sensor node. In this paper, we first discuss the basics of MAC design for WSNs and present a set of important MAC attributes. Subsequently, we present the main categories of MAC protocols proposed for WSNs and highlight their strong and weak points. After briefly outlining different MAC protocols falling in each category, we provide a substantial comparison of these protocols for several parameters. Lastly, we envision future research directions on open issues in this field that have mostly been overlooked.

1. INTRODUCTION

The pervasiveness, self-autonomy and self-organization of low-cost, low-power and small-sized WSNs [1 - 6] have brought a new perspective to the world of wireless communication. They are emerging as an ideal candidate for several daily-life applications, especially in monitoring and controlling domains. The demands placed on such type of networks are expending exponentially with the increase in their dimensions. The development of new hard-ware, software and communication technology and continuous refinements of current approaches is also pushing this domain even further. However, all these unique characteristics along with the limited resources have made WSN a challenging network. Integrating sensing, processing and communication functionalities into a sensor node has added a lot of complexities. Moving from sensors with only few hours of life time to one with many years of life time demands several iterations of energy efficient techniques.

The MAC protocol for WSNs can save a substantial amount of energy by judiciously controlling the functionalities of radio, which is the most power-depleting component of resource-scarce nodes. The nodes of WSNs share a wireless medium and communicate with each other usually via multi-hop routes in a scattered, dense and rough sensor field. The MAC protocol also manages the shared-medium and creates a basic network infrastructure for nodes to communicate with each other. Thus it provides a self-organizing capability to the nodes and tries to enforce singularity in the network by letting the sender and receiver communicate with each other in a collision-free fashion. Therefore, the MAC protocol helps fulfilling important design objectives of WSNs by specifying how nodes employ the radio to conserve energy, share the channel and avoid collision in correlated and broadcasting environments.

1. 1 MAC RESPONSIBILITIES

The primal task of any MAC protocol, in general, is to govern the fair access of nodes on a shared medium in an efficient way in order to achieve good individual throughput and better channel utilization [7]. However, dense deployment of nodes, collaboration among nodes

*, ****, *****Assistant Professor, Department of CSE, Quaid-e-Awam University of Engineering, Science and Technology, Nawabshah, Sindh

**Associate Professor, Department of IT, Quaid-e-Awam University of Engineering, Science and Technology, Nawabshah, Sindh

*** Assistant Professor, Department of IT, Quaid-e-Awam University of Engineering, Science and Technology, Nawabshah, Sindh

rather than competition, dispersed applications, often decentralized control and volatile communication links make WSNs quite a different type of network. The responsibilities of a MAC protocol for WSNs therefore differ considerably as of the other wired or wireless networks. Fairness, higher channel utilization and individual throughput are not as important for a WSN MAC protocol as the energy conservation, collaboration and collective information among nodes.

Additionally and as per application requirement, provision of timeliness, reliability, scalability and non-synchronized operation may also play an important role in designing a MAC protocol for WSNs. Furthermore, an ideal MAC protocol ensures self-stabilization, graceful adaptation to topology and traffic changes, an acceptable delivery ratio and low overhead and error rate for a WSN.

2. MAC CHALLENGES FOR WSNs

The design of a MAC protocol for WSNs is challenging due to limited energy resources, low transmission ranges, compact hardware, event based network behavior, self-configuration and high redundancy factors. Moreover, by virtue of a wireless broadcast medium, WSNs inherit all the problems like interference, fading, path loss, attenuations, noise, and high error-rates [8 - 9]. Evidently, a lot of research work related to the MAC designing for WSNs revolves around energy efficiency. Other goals like latency, packet delivery ratio, and adaptation to traffic conditions and scalability are often traded-off in favor of energy efficiency. The main sources of energy waste in WSNs that a MAC protocol has to dealt with are idle listening, collision, overhearing, over-emitting and control packet overhead [10].

Along with energy efficiency, several WSN applications may need delay bound operations. However, unlike traditional distributed systems, the timeliness guarantee for WSNs is more challenging. They interact directly with the real world, where the physical events occur in an unpredictable manner with different traffic and delay requirements. Duty cycling, dynamic topology and limited memory and computation power also restrict the design space we could trade off.

As a result, many existing architectures and protocols for traditional wireless networks such as IEEE 802.11 and Blue-tooth are not suitable for WSNs as they usually target higher data rates with less emphasis on energy issues. Therefore, novel MAC approaches supporting special requirements of such challenging network are being developed.

3. COMMON MAC APPROACHES FOR WSNs

There is not any generic best MAC protocol for WSNs; the design choice mainly depends on the nature of the application. The stringent design requirements of a MAC protocol for WSNs can be met by a plethora of approaches. The most widely used approaches in designing such MAC protocols with their implications are outlined below.

3. 1 DUTY CYCLING

A WSN generally generates much less data traffic and sends very small data frames as compared to traditional wireless or wired networks. The sensor nodes therefore remain idle most of the time either waiting for their periodic turn to generate data or listening the idle channel for an event to occur. Since the radio consumes as much energy during idle listening as in receiving data packets, switching it in low-power sleep mode and waking up shortly to listen the medium can significantly conserve the energy of nodes. The sum of the sleep period and the listen period is called wake-up period, whereas the ratio of the listen period to the wake-up period is called duty cycle of the node.

Duty cycling significantly increases system lifetime of a dense WSN by reducing idle-listening and over-hearing. However, the selection of an optimal duty cycle value is not an easy task. Long sleep period may induce extra per-hop delay since a sending node needs to wait until the receiver wakes up and accepts the packets. More frequent switching of radio between sleep and awake modes, i.e., lower sleep phases also outweighs the benefits of duty cycling. Hence, the optimal selection of duty cycle value is a critical step towards achieving the desired system performance.

3.2 TOPOLOGY CONTROL

The aim of topology control is to build a reduced topology by dynamically changing transmitting range of nodes. In this way energy of nodes can be saved while keeping the network connectivity and coverage intact [11]. As transceivers are one of the primary sources of energy consumption in WSNs, topology control reduces energy consumption by forcing packets to travel through multiple hops. The topology control mechanism reduces energy consumption by reducing collisions, contentions and exposed terminal problems. However, idle listening, overall latency, complexity and increased packet loss probability remain core issues with this mechanism.

3.3 SCHEDULING AND SYNCHRONIZATION

Several WSN MAC protocols assume that nodes follow a fix schedule to switch their radios between wake-up and sleep modes. They also assume that nodes are timely synchronized. However, in reality such time synchronization in dynamic and resource-limited WSNs is very difficult to achieve as it induces a lot of overhead and may need extra hardware and/or complex algorithms. Collisions and retransmissions increase dramatically if all nodes wake up simultaneously resulting in higher energy waste and packet delay. Therefore, it is wise to use the random and non-synchronized wake-up and sleep schedules for WSN nodes.

3.4 CROSS-LAYERING

Most of the time, the conventional layered architecture has been followed by the researchers to design WSN MAC protocols. With very limited resources available for WSNs, a trend of cross-layer designing is emerging in order to achieve aggregate optimization among different layers. Unlike layered networks, WSNs cannot afford significant layered overhead due to their limited energy, storage and processing capabilities. Moreover, application-aware communication and low-power radio considerations motivate for the cross-layer architecture for WSNs. Recent studies in [12 - 16] affirm improvement in WSN performance by using cross-layering.

3.5 TIMELINESS SUPPORT

No doubt, energy efficiency in WSNs has always remained a prominent objective of researcher. However, with ever increasing applications of WSNs in many diverse fields, new concept for offering timeliness related Quality of Service (QoS) is inevitable. Nevertheless, limited resources, low node reliability, dynamic network topology and direct interaction with the physical world make hard timeliness in WSNs very difficult. As a result, the probabilistic based soft timeliness guarantee in many applications of WSNs is mostly permissible.

4. CLASSIFICATION OF WSN MAC PROTOCOLS

The WSN MAC protocols can be classified depending on how nodes access the channel into the general categories of contention based, scheduling based, channel polling based, and hybrid protocols [17].

4.1 CONTENTION BASED MAC PROTOCOLS

With the contention-based Carrier Sense Multiple Access (CSMA) method, the transmitting node, before any transmission, first senses the carrier. If the carrier is found idle, it starts with its transmission, otherwise defers the transmission for some random time, which is usually determined by the back-off algorithm. Such MAC protocols consume less processing resources and are suitable for event-driven WSN applications. They are flexible to network scale and dynamics as no clustering and topology information is required. However with this approach, the transmission is purely handled by the sender and the problem of hidden- and exposed-terminal may occur resulting in collisions, overhearing, idle listening and less throughput. Moreover, in many proposals, authors consider that contention time of nodes is synchronized and based on a schedule, i.e., at each periodic interval, all neighboring nodes wake up simultaneously [18], [19], [20]. That would incur all the mentioned problems of synchronization in a WSN.

The well-known protocols working under this scheme are briefly outlined below.

(a) S-MAC: The design of the Sensor-MAC (S-MAC) [18] was one of the first attempts to significantly reduce idle listening; collisions and overhearing in WSNs by putting nodes in listen and sleep periods. S-MAC organizes the schedules of neighboring nodes by letting nodes share common listen periods according to a schedule. This requires formation and maintenance of synchronization among nodes. In order to reduce the hidden-terminal effect, S-MAC uses the RTS/CTS

handshake scheme. To minimize costly retransmissions, S-MAC fragments long messages into short frames and sent them in a burst. The RTS/CTS is only required before transmitting the first short frame.

S-MAC is rigid for a predefined set of workloads as there is no mean to adapt the length of listen and sleep periods with changing traffic conditions. As discussed earlier, the formation, maintenance and compliance of synchronization has serious consequences in WSNs. Longer and fixed sleep periods of S-MAC have serious impact on system latency. Moreover, the S-MAC nodes may follow more than one schedule, which results in higher energy consumption via idle listening and overhearing. With fragmentation in S-MAC, overhead and retransmission can be reduced, but it comes at the expense of unfairness since a node reserves the channel for a whole burst duration.

(b) T-MAC: The Time-out MAC (T-MAC) [19] protocol improves the energy efficiency of S-MAC by adaptively cutting down the listen period, which ends immediately if no activation event has occurred for a threshold period *TA*. The comparison between S-MAC and T-MAC shown in Figure 1 confirms this improvement. However, T-MAC could result in the early sleep for nodes, i.e., a node, specially the third hop one, goes to sleep mode when a neighbor still has messages for it. Though T-MAC saves more energy than S-MAC, it comes at the cost of reduced throughput, packet loss and higher latency. T-MAC also suffers from synchronization and scaling problems.

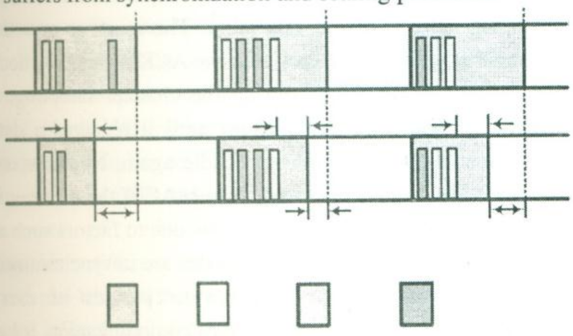

Figure 1: T-MAC vs. S-MAC

4.2 SCHEDULING BASED MAC PROTOCOLS

Scheduling based schemes assign collision-free links to each node in the neighborhood. The links may be assigned as time slots (TDMA), frequency bands (FDMA), or spread spectrum codes (CDMA). However, due to the complexities incurred with FDMA and CDMA schemes, TDMA schemes are preferred as scheduling methods for WSNs. A schedule in such schemes regulates which participant may use which resource at what time. A node can only access its allocated time slot and does not need any contention with its neighbors.

The cardinal advantages of scheduling based schemes include minimum collisions, less overhearing and implicitly avoidance of idle listening. They also provide a bounded and predictable end-to-end delay. However, the average queuing delay is much higher as a node has to wait for its allocated slot before accessing the channel. Overhead and extra traffic required in setting up and maintaining synchronization among nodes, no mean to adapt with varying traffic and topology conditions, reduced scalability, low throughput and no peer-to-peer communication are the major concerns with these schemes.

(a) Leach: A mostly scheduled based Low-Energy Adaptive Clustering Hierarchy (LEACH) protocol [21] divides a dense and homogeneous WSN into clusters each supervised by a cluster head. The cluster head is responsible for creating and maintaining TDMA schedules, communicating with its cluster members and forwarding the received messages to the sink node. LEACH also uses a randomized rotation mechanism for selecting a cluster head and tries to distribute the energy among nodes in an evenly manner. The cluster head of LEACH has to perform highly computational and energy consuming tasks and remains always awake, therefore the chances of a cluster head to die earlier are high. LEACH considers that all the cluster heads are within the range of the sink node. The lack of such multi-hop communication capabilities severely limits the network scalability. The channel under-utilization occurs with LEACH as it considers that nodes always have data to send during their allotted time.

(b) Trama: The TRaffic-Adaptive Medium Access (TRAMA) protocol [22] is mostly a TDMA based protocol. It schedules nodes on a distributive manner based on some traffic information. Each node computes its own priority and the priority of all its two-hop neighbors for each time slot. TRAMA uses neighborhood as well as schedule information to select the sender and

receivers for the current time slot, letting all other nodes to go to sleep mode. TRAMA also attempts to reuse slots that are not used by the selected transmitter.

The reuse of time slots and the utilization of neighborhood and traffic information are the positive features of TRAMA. The simulation results presented in [22] show higher percent-age of sleep time, less collision probability, and better data delivery with TRAMA as compared to S-MAC and IEEE 802.11. However, higher computation, large queuing delays and ineffective channel and memory utilization are the major concerns for a TRAMA based WSN.

4.3 CHANNEL POLLING BASED MAC PROTOCOLS

With the channel polling scheme, also known as preamble sampling or Low Power Listening (LPL), a sending node prefixes data packets with extra bytes called a preamble and sends it over the channel to ensure that the destination node would detect the radio activity and wake up before the actual payload is sent. On a wake-up, if radio activity is detected, the receiver turns on its radio, otherwise goes back to sleep mode until the next polling interval. To avoid deafness, a sender prefixes preamble at least as long as the check interval of the receiver to ensure that the receiver wakes up and performs channel sampling at least once while the preamble is being sent [23]. Figure 2

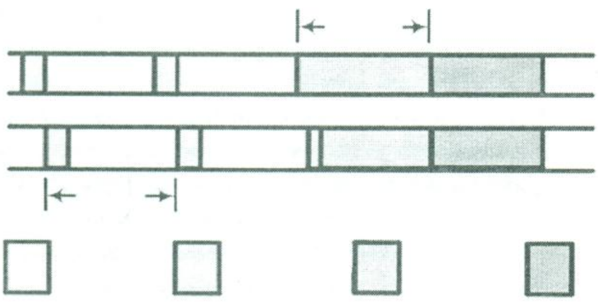

Figure 2: Channel Polling in WSNs

shows an example how channel polling works in WSNs. Channel polling based protocols do not need synchronization or clustering. Receivers consume significantly less energy as they wake up for very short period of time. However, the sender needs to send out a long and extended preamble before each data packet. Another issue is the limitation of the duty cycle value. Lowering the duty cycle extends the check interval. That is good from the receiver point of view but it significantly increases the transmission cost in the shape of long and extended preambles at the sender side. Therefore, this long preamble scheme results in unnecessary energy consumption both at the receiver and sender ends, overhearing at non-target receivers and excessive latency at each hop. These issues can be tackled by using short preambles, adaptive duty cycle values and by minimizing redundancy [24].

(a) B-MAC: Berkeley MAC (B-MAC) protocol [23] is one of the initial MAC protocols working on the traditional long preamble scheme, where the transmitting node precedes the data packet with a preamble that is slightly longer than the check interval of the receiver. On wake-up, if the node detects a preamble, it remains awake to receive the whole preamble. If the preamble is destined to this node, it further extends its wake-up time to receive the data packet; otherwise goes back to sleep mode. B-MAC uses an improved version of the Clear Channel Assessment (CCA) to determine whether the channel is clear. With an extended preamble, B-MAC reduces duty cycle and minimizes idle listening, particularly when there are no packet exchanges. It supports on-the-fly tuning of services by providing bidirectional interfaces to enable or disable services. However, B-MAC incurs all the mentioned problems of the long preamble scheme.

The WiseMAC [25] protocol tries to minimize the preamble length by letting a node learn about the awake periods of its neighbors. A sending node sends a preamble just before the receiving node wakes up and hence keeps the preamble length at minimum. The receiver puts the time of its next awake period in the ACK frame. If a node finds the medium busy during the channel sampling, it continues listening the medium until it receives a data packet or the medium becomes idle again. Nevertheless, over-emitting can occur with WiseMAC if the receiver is not ready at the end of the preamble due to factors such as interference or collision. Since nodes are unsynchronized, the transmitter has to keep awake periods of every neighbor and in case of a broadcast communication, it has to deliver the same packet many times to each neighbor. This redundant transmission leads to higher latency and energy consumption for nodes.

(b) AREA-MAC: The Asynchronous Real-time Energy-efficient and Adaptive MAC (AREA-MAC) protocol [24] re-visits the energy, timeliness, adaptability,

synchronization and redundancy problems of WSNs by using the short preamble technique. The sender sends out a stream of short preambles with a short spacing and turns its radio to receive mode in between in order to receive the pre-ACK from the intended receiver. The sender sends the data packet as soon as it receives the pre-ACK. This minimizes the chances of the data packet being dropped as the sender and receiver communicate via a 'pre-established' link. Each short preamble contains information such as the source address, destination address, sequence number and message type of the forthcoming data packet and the data-to-follow bit to inform the receiving node whether the sender has more data packet(s) waiting in its queue to be transmitted. Figure 3 shows the basic working of AREA-MAC protocol.

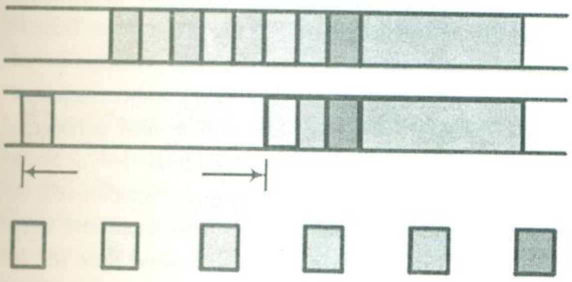

Figure 3: Basic working of AREA-MAC protocol

Short preambles unified with the pre-ACK mechanism (by using the source and destination addresses) impede several problems of the long preamble technique such as unnecessary energy consumption both at the receiver and sender ends, excessive latency at each hop, increased collision probabilities with the increased transmission and reception lengths, over-hearing at non-targeted receivers and bandwidth waste on the broadcast medium. The sequence number of the forthcoming data packet present in the preamble helps sensor nodes in reducing the number of redundant data packets. AREA-MAC considers different message types to support both normal and real-time traffic, which is indicated by the message type information of the preamble. The receiving node can also adapt its wake-up schedule in accordance with the sender that has enabled its data-to-follow bit, which further decreases packet latency and energy consumption of sensor nodes.

4.4 HYBRID MAC PROTOCOLS

Hybrid MAC protocols combine the strength of two or more different MAC schemes in order to achieve a joint improvement. They usually combine a synchronized protocol with an asynchronous one. Though such protocols aggregate the advantages of two or more schemes, they also carry, among other, scaling and increased complexity problems as they have to maintain two or more different working modes.

(a) IEEE 802.15.4: The IEEE 8021.5.4 standard [26] defines the PHY and MAC layers for a low cost, low power and low rate wireless personal area network (LR-WPAN). The standard supports both star and peer-to-peer operation with Fully and Reduced Function Devices (FFDs and RFDs). Together with ZigBee, which provides the upper (network and application) layers, 802.15.4 defines a full protocol stack suitable for several surveillance, home automation, health care, industrial and agricultural related applications of WSNs.

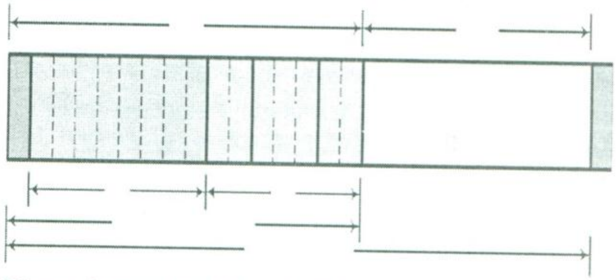

Figure 4: IEEE 802.15.4 MAC Superframe

The format of the MAC superframe is defined by the PAN coordinator (FFD) and is shown in Figure 4. The superframe is divided into 16 equally sized slots and the beacon is sent in the first slot to synchronize attached devices, to identify the PAN and to describe the overall structure of the superframe. The superframe can be further divided in two parts; Contention Access Period (CAP) and Contention Free Period (CFP). Any device wishing to communicate during the CAP period competes with other devices using a slotted CSMA/CA mechanism. For time and/or bandwidth critical applications, the PAN coordinator may dedicate contention-free TDMA-like Guaranteed Time Slots (GTS) portion of the CFP to devices. The combination of CSMA and TDMA makes 802.15.4 MAC a hybrid protocol.

Though 802.15.4 MAC protocol fulfils many of the WSN

Table 1: Comparison of different WSN MAC protocols for their support to different parameters

Protocol	Type	Energy eff.	Delay eff.	Async.	Adaptive	Scalable
S-MAC	CSMA	yes[1]	no	yes[2]	yes[1]	yes[1]
T-MAC	CSMA	yes[1]	no	yes[2]	yes	yes[1]
LEACH	TDMA	yes	no	no	no	no
TRAMA	TDMA	yes[1]	no	no	yes	no
B-MAC	Ch. Polling	yes[1]	no	yes	yes[1]	yes
WiseMAC	Ch. Polling	yes[1]	yes[1]	yes	yes	yes
AREA-MAC	Ch. Polling	yes	yes	yes	yes	yes
802.15.4	Hybrid	yes[1]	yes[1]	yes[3]	no	no
Z-MAC	Hybrid	yes	no	no	yes	no

[1] Suboptimal, can be improved [2] Uses common listen periods [3] Topology dependent

requirements, it endures the limitations, especially for timeliness, energy and bandwidth critical applications, and its performance can certainly be improved. All these limitations and their proposed solutions, along with the detailed working of 802.15.4 are elaborated in [28].

(b) Z-MAC: The Zebra MAC (Z-MAC) [29] protocol is a hybrid scheme that aggregates the positive aspects of TDMA and CSMA while offsetting their weaknesses. Z-MAC is a traffic adaptive protocol as it switches to CSMA under low traffic conditions in order to achieve high channel utilization and low delays. Under high traffic conditions it switches back to TDMA to achieve high channel utilization, fairness and fewer collisions. Unlike the traditional TDMA schemes, a node using Z-MAC can also utilize slots assigned to other nodes. Z-MAC provides a simple two-hop synchronization scheme where the transmitting node adapts the frequency based on its current data rate and resources. Hence, Z-MAC offers better performance under different time-varying channel/slot conditions and failures. However, during the start up phase, Z-MAC requires global time-synchronization, which certainly is a heavy burden for light-weight nodes. Complexity in maintaining both CSMA and TDMA modes, contention among nodes to gain access of the slots owned by other nodes, collisions and bandwidth under-utilizations are the other issues with Z-MAC.

5. COMPARISON OF DIFFERENT MAC PROTOCOLS

Having discussed main categories of accessing the channel in WSNs and different MAC protocols falling in each category, a comparison of these protocols for their support to energy efficiency, timeliness, asynchrony, adaptability and scalability factors is presented in Table I. It is clear from the table that most of the protocols do not support all of these parameters. They either support a parameter partially or trade-off with another parameter. Some of the protocols are suboptimal for a given parameter and can be improved further. Protocols such as S-MAC and T-MAC assume common listen and sleep periods for all their nodes, hence they need some sort of synchronization among nodes. As discussed, to create, manage and maintain synchronization in a resource scarce WSN is always a challenging task. The AREA-MAC protocol intends to address almost all the considered parameters in an efficient manner.

6. FURTURE RESEARCH DIRECTIONS

The research community has witnessed intense research related to the MAC design for WSNs over the last years. Various MAC protocols target different objectives and have different performance priorities. The most visible and prime consideration of almost all of them is the issue of energy efficiency. Other typical performance metrics like latency, adaptability to traffic and topology conditions, scalability, fairness, throughput and bandwidth utilization are mostly overlooked or dealt as secondary objectives due to the school of thought that nodes are densely deployed and they collaborate with each other rather than compete. However, with the advent of new Micro Electro-Mechanical Systems (MEMS) technologies and energy harvesting techniques and with the dynamic increase in several WSN related applications, the research community is set to experience many diverse directions in this domain. For numerous applications of WSNs, some of these metrics may temporarily outweigh energy efficiency. Hence, energy consumption, which no doubt is the most critical parameter for WSNs performance, should not be the only focal point in designing a MAC protocol.

For medical urgency, surveillance, security, terrorist attacks, home automation, flood, fire and seismic detection applications, the provision of timeliness is as crucial as saving energy. For example; a sensor node embedded in an e-textile worn by patients should automatically but timely alert doctors or emergency services when a patient suffers from a severe disease. In this case, the importance of delivery ratio may also be increased as one disease could immediately result in other diseases and body sensors deployed on or near different body parts need to urgently inform medical personnel about the relative body part.

Last but not least, selecting a proper hardware scheme has a lasting impact on the performance of a MAC protocol and ultimately on a whole WSN system. Support for multi-channel hardware, balancing an appropriate memory size, usage of wake-up radio and selection of a packet- or bit-based radio are the important factors [10].

7. CONCLUSIONS

Although a lot of MAC protocols for WSNs have been proposed over the last years, the selection of a proper MAC protocol usually depends on the application. This paper manifests different factors and techniques that need definite consideration while designing a MAC protocol for WSNs. To cope with most of the energy related issues such as idle listening, collisions, overhearing, control packets and over-emitting, an eminent amount of research work supports duty cycling in WSNs. However, this duty cycling results in high latency and low throughput and a deep consideration is required to select a proper duty cycle value.

Along with the detailed working of each category and protocols falling in, their advantages as well as disadvantages are also discussed in detail. The channel polling based mechanism of MAC designing provides better energy consumption but the traditional long preamble schemes have several limitations that can be handled by using short preamble scheme. A substantial comparison of these protocols for different parameters is also presented in the paper. At the end, future research directions in designing a MAC protocol are envisioned, where we conclude that energy efficiency even though being the most critical metric is not sufficient to address. Factors like timeliness, scalability, asynchrony, delivery ratio and adaptability to traffic and topology changes may also need important considerations as per requirement of the application.

REFERENCES

[1] H. Karl and A. Willig, Protocols and Architectures for Wireless Sensor Networks. John Wiley and Sons Ltd, 2006.

[2] Pardeep Kumar & Mesut Günes, "Medium Access Control Protocols in Wireless Sensor Networks: Design Space, Challenges, and Future Directions" in 'Wireless Sensor Networks and Energy Efficiency: Protocols, Routing and Management' book, IGI Global Publisher, 2012.

[3] Pardeep Kumar & Mesut Günes, "MAC Protocols for Low-latency and Energy-efficient WSN Applications", Technical Rep. TR-B-08-18, Free University of Berlin, Germany, December 2008.

[4] S. Misra, I. Woungang, and S. C. Misra, Guide to Wireless Sensor Networks. Springer-Verlag London Limited, 2009.

[5] Pardeep Kumar, Mesut Günes, Qasim Mushtaq & Bastian Blywis, "A Real-Time and Energy-Efficient MAC Protocol for Wireless Sensor Networks", Sixth IEEE International Conference on Wireless and Optical Communications Networks, Cairo, Egypt, April 2009.

[6] M. Tubaishat and S. Madria, "Sensor networks: an overview," IEEE Potentials, Vol.22, Issue2, pp. 20–23, April 2003.

[7] M. A. Labrador and P. M. Wightman, Topology Control in Wireless Sensor Networks. Springer Science and Business Media B.V., 2009.

[8] Tse and P. Viswanath, Fundamentals of Wireless Communication. Cambridge University Press, 2005.

[9] V. Garg, Wireless Communications and Networking. Elsevier - Morgan Kaufmann Publishers, 2007.

[10] Bachir, M. Dohler, T. Watteyne, and K. Leung, "MAC essentials for wireless sensor networks," IEEE Communications Surveys and Tutorials, vol. 12, Issue 2, pp. 222–248, 2010.

[11] P. Santi, "Topology control in wireless ad hoc and sensor networks," ACM Computing Surveys, vol. 37, pp. 164–194, June 2005.

[12] T. Melodia, M. C. Vuran, and D. Pompili, "The State of the Art in Cross-layer Design for Wireless Sensor Networks," EuroNGI Workshops on Wireless and Mobility. Springer Lecture Notes in Computer Science 3883, July 2005.

[13] V. Kawadia and P. R. Kumar, "A Cautinary Perspective On Cross-Layer Design," in IEEE Wireless Communication Magazine, February 2005.

[14] J. Haapola, Z. Shelby, C. Pomalaza-Raez, and P. Mahonen, "Cross-Layer Energy Analysis of Multi-hop Wireless Sensor Networks," in EWSN'05, 33–44, 2005.

[15] L. V. Hoesel, T. Nieberg, J. Wu, and P. J. M. Havinga, "Prolonging the lifetime of wireless sensor networks by cross-layer interaction," in IEEE wireless communication, vol. 11, pp. 78–86, December 2004.

[16] P. Kumar, M. Gunes, Q. Mushtaq, and J. Schiller, "Performance evaluation of area-mac: A cross-layer perspective," in The Fifth International Conference on Mobile Computing and Ubiquitous Networking (ICMU 2010), (Seattle, USA), April 2010.

[17] K. Klues, G. Hackmann, O. Chipara, and C. Lu, "A component-based architecture for power-efficient media access control in wireless sensor networks," The 5th International Conference on Embedded Networked Sensor Systems (SenSys'07), November 2007.

[18] W. Ye, J. Heidemann, and D. Estrin, "Medium access control with coordinated adaptive sleeping for wireless sensor networks," IEEE/ACM Trans. Net., vol. 12, no. 3, pp. 493–506, June 2004.

[19] T. van Dam and K. Langendoen, "An adaptive energy-efficient mac protocol for wireless sensor networks," 1st ACM Conf. on Embedded Networked Sensor Systems (SenSys), pp. 171–180, November 2003.

[20] P. Lin, C. Qiao, and X. Wang, "Medium access control with a dynamic duty cycle for sensor networks," IEEE WCNC, vol. 3, pp. 1534–1539, March 2004.

[21] W. Heinzelman, A. Chandrakasan, and H. Balakrishnan, "An application-specific protocol architecture for wireless microsensor net-works," IEEE Transactions on Wireless Communications, vol. 1, no. 4, October 2002.

[22] V. Rajendran, K. Obraczka, and J. J. Garcia-Luna-Aceves, "Energy-efficient, collision-free medium access control for wireless sensor net-works," ACM SenSys, Los Angeles, CA, November 2003.

[23] J. Polastre, J. Hill, and D. Culler, "Versatile low power media access for wireless sensor networks," 2nd ACM Conf. on Embedded Networked Sensor Systems (SenSys 2004), Baltimore, MD, pp. 95–107, November 2004.

[24] P. Kumar, M. Günes, Q. Mushtaq, and B. Blywis, "A real-time and energy-efficient mac protocol for wireless sensor networks," Interna-tional Journal of Ultra Wideband Communications and Systems (IJUW-BCS), Vol. 1, Issue. 2, pp. 128 – 142, 2009.

[25] I.El-Hoiydi and J. Decotignie, "WiseMAC: An ultra low power mac protocol for the downlink of infrastructure wireless sensor networks," 9th IEEE Symposium on Computers and Communication, ISCC04, pp. 244–251, June 2004.

[26] "IEEE 802.15.4-2006: MAC and PHY specifications for LR-WPANs," http://ieee802.org/15/pub/TG4.html.

[27] "Zigbee" http://www.zigbee.org.

[28] P. Kumar, M. Günes, A. A. Almamou, and I. Hussain, "Enhancing IEEE 802.15.4 for low-latency, bandwidth and energy critical wsn applications," October 2008.

[29] Rhee, A. Warrier, M. Aia, and J. Min, "ZMAC:a hybrid MAC for wireless sensor networks," 3rd ACM Conf. on Embedded Networked Sensor Systems (SenSys'05), November 2005.