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Literature Review of Energy Efficient Transmission in Wireless LANs by Using Low-Power Wake-Up Radio

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***Abstract*-Power consumption is a key consideration in every WLAN MAC protocol design for wireless devices and extending battery life requires more efficient power management scheme considering that Carrier sensing by WLAN modules consumes enormous amount of power. Researchers over the years have proposed and implemented various schemes using a low-power Wake-up Radio for carrier sense which has proven to be effective. In this paper, a comprehensive literature review of the research progress in WuR-based energy saving is presented. This paper compares the various protocols already proposed for mitigating latency and energy consumption in WLAN networks and provides synthesis of wake-up radio (WUR) based carrier sensing approaches with analysis and discussions of merits and limitations of each technique. The operation principles of duty-cycle and wake-up radio bases MAC protocols were looked into in relation to how they affect energy efficiency and latency reduction.**

Index Terms – Wake-up Radio, Energy Efficiency, MAC protocol, WLAN module

I. INTRODUCTION

The fast growth of data traffic in cellular networks today requires that most non-real-time traffic be transmitted through a wireless local area networks (WLANs) warranting WLAN modules to be implanted into mobile devices such as smartphones and tablets. Due to the power-hungry nature of WLAN module and considering the fact that a mobile device is driven by a battery with limited capacity, it therefore becomes pertinent to reduce power consumption. A WLAN module is expected to receive messages instantly by staying in the constant awake mode (CAM) but idle waiting leads to much power consumption. This led researchers in the industry to conceive and try-out various methods of solving this issue among which duty-cycling and later wake-up radio (WuR) integration approach played prominent role but not without their shortcomings. Using a Wake-up radio with the wireless LAN (WLAN) requires that each power-hungry WLAN module be equipped with a low-power wake-up radio receivers (WuRx) which receives a wake-up message (WuM) and activates its co-located WLAN module on demand thereby carrying out all the carrier sense operation responsible for the bulk of power consumption in the WLAN module.

A. Duty Cycling

The fact that the power utilization of a WLAN module while transmitting is almost same as in the listening mode leaves much to be desired in term of energy efficiency of Wi-Fi devices. To improve the situation, the Duty-Cycling technique came in handy allowing the power-hungry module to wake up only when it has to receive or transmit data, if not it remains in the sleep mode thereby saving energy as shown in Figure 1.

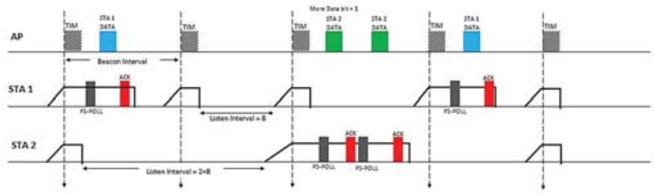

Figure 1: Legacy Duty-Cycle power save

However, the sleep time could not be considerably extended since the module would have to:

i. Intermittently listen to ongoing transmissions over the channel even if there is no data destined for it. However, idle listening contributes to power consumption considering that eighty percent of time is spent in this state as evidenced in [27].
ii. Receive data that are not destined for it (overhearing) which had to be discarded thereby expending energy undesirably as stated in [33].

Aside the issue of inefficient energy consumption, the Duty-Cycle protocols also promotes substantial data latency since the module cannot communicate in the sleep mode meaning that some packets may have to be re-transmitted over and over before they can be received.

Also, this technique requires a high level of synchronization between the AP and the STA contributing to the protocol overhead. Some of the approaches adopted in the duty-cycle technique include:

i. In the unicast situation, every STA establishing a connection with the AP is allocated an association identifier (AID) in the TIM [28]. When a STA in PSM finds out that frames are buffered at the AP and it is intended for it, PS-Poll frame is sent to the AP requesting the transmission of the stored data as soon as possible and it afterward sends an ACK frame to the AP to acknowledge receipt. This technique saves power by ensuring that STA without data buffered at the AP goes back to sleep mode.

ii. **Traffic Indication Map (TIM) broadcast is** a service that enables a non-access-point (non-AP) station (STA) to request periodic transmission of a TIM frame by the AP. TIM frames have shorter duration than Beacon frames and can be transmitted at a higher physical layer (PHY) rate, which allows the STA to save additional power while periodically checking for buffered traffic in standby mode, relative to the power consumed if the station (STA) were to periodically wake up to receive a Beacon frame [30]. This approach has proven to be more helpful in improving power management in WLAN as demonstrated in [20, 29].

iii. **APSD** was introduced with IEEE 802.11e, it is a technique in which the AP transmits numerous data frames to the same STA during a single Service Period (SP). APSD defines two delivery mechanisms, namely *unscheduled APSD* (U-APSD) and *scheduled APSD* (S-APSD); For the S-APSD, the STA wakes up to communicate data at a scheduled time making it possible for AP to transmit without signaling while for the U-APSD, the STA triggers an SP whenever it sends a trigger frame enabling the AP to send the buffered data. It also requires high degree of synchronization.

iv. The power save multi-poll mechanism was introduced with the IEEE 802.11n. It provides a time schedule that is used by an access point (AP) and its stations (STAs) to access the wireless medium [30] and allows an AP to schedule uplink and downlink for STAs by broadcasting a PSMP frame.

v. Transmission Opportunity (TXOP) technique permits STAs to switch between sleep and awake. STAs in this mode goes to sleep when other STAs or the AP transmit [31] (i.e., during a TXOP) as informed by the virtual carrier sense information in management and overheard control and data frames.

Limitations: Despite the fact that Power Save Multi-Poll (PSMP) is an improvement on Automatic Power Save Delivery (APSD) while the latter is also an improvement on the legacy power-save mode (PSM), these techniques involves listening to the channel which undermines optimal performance and energy saving in high density bidirectional traffic network considering that beacons carries identifiers which limits deployment on a large scale and carrier sensing cause additional energy consumption for the STAs. It also may not be possible for some STAs to go to sleep under the TXOP scheme where the duration of the TXOP is less than what the STA needs to sleep and wake up [31]. Duty-cycle techniques save energy but their design gaps prompted researchers to propose and design numerous improved MAC protocols aimed at prolonging the battery life of Wi-Fi devices including the implementation of wake-up radios.

B. WLAN Module with Wake-up radio

A wake-up receiver shares the same antenna with WLAN module which reduces hardware cost and also shares common ISM band (2.4GHz/5GHz) using a compatible MAC protocol as proposed in [4, 12, 33]. To lower the power consumption of the WuR as seen in [12, 19, 32], RF envelope detection does the frequency conversion eliminating the need for RF oscillators which consumes much power, On-Off-Keying (OOK) modulation scheme [32] and RF envelope detection is used instead of coherent detection and no error correction is done. However, issues of Co and Adjacent channel interference and high false wake-up probability are some of the research gaps that has kept scholars busy as [12, 16] made it evident. The architecture of a wake-up radio is shown in Figure 2 indicating both receiver and the transmitter. The WuTx generates the Wake-Up ID (WID) of the STA it intends to wake up, encode it, modulate it on the WLAN signal using the OOK scheme, spread it over the spectrum (OFDMA) and sends the wake-up message (WuM) over the channel soon as it is sensed to be idle. On the receiver side, the WuM is extracted by the RF BPF, it is then amplified for the envelope detector to retrieve the WID, then "WID-matching" triggers the WLAN module to wake as [12] proposed. However, in [15, 19], the WLAN module of the AP is configured to act as the transmitter.

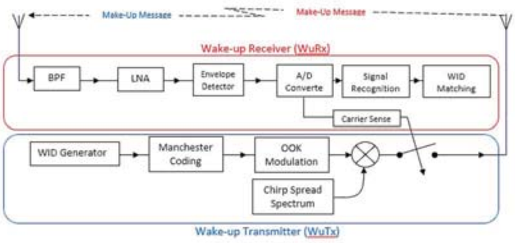

Figure 2: Wake-up Radio Architecture

C. The Wake-Up Message (Wum)

A wake-up message (WuM) frame as shown in Figure 3 is composed of a frame header. It also comprises of an optional address field which could be unicast of broadcast based, a payload field that holds the application data, command and extra instructions given by user, and error detection field required in frame check sequence (FCS) using cyclic redundancy codes (CRC) as [33] proposed.

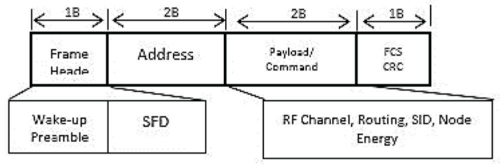

Figure 3: Wake-up Message packet structure (from [33])

Different communication medium can also be used for WuM transmission such as RF-based Medium: where frequencies in the range of ≈3KHz to GHz is use, Acoustic medium: where ultrasonic and audio signals are used and Optical medium where lasers are utilized for sending WuM, proposed in [33, 34].

Considering the work of Suhua Tank *et al*. [12], if the duty ratio of a STA is represented as O_{STA} during which the STA is active but its WuRx is off, consuming P_{STA} power from operations of CPU, memory and so on besides power required to transmit packet, and given that that the STA rest period is 1-O_{STA} in which the STA is in sleep mode while the WuRx is active with power consumption of P_{WuRx}, Power consumption ratio of the WuRx can be computed as r_{WuRx}

$$r_{WuRx} = \frac{\text{Power consumed by the wake up receiver}}{\text{average power consumed by the whole STA system}}$$

Power consumed by the wake-up receiver is =

$$(P_{WuRx}) \times (1 - O_{STA}) \quad (1)$$

the average power consumed by the whole STA system is =

$$(P_{STA} \times O_{STA}) + \left(P_{WuRx} \times (1 - O_{STA})\right) + (P_{STA} \times FPP \times (1 - O_{STA}) \quad (2)$$

Therefore

$$r_{WuRx} = \frac{(P_{WuRx})\times(1-O_{STA})}{(P_{STA}\times O_{STA})+(P_{WuRx}\times(1-O_{STA}))+(P_{STA}\times FPP\times(1-O_{STA})} \ldots (3)$$

The ratio expressed as η of power consumed by a WuRx enabled STA to that of a STA without the WuRx can be expressed as shown below, it determines how much reduction in power consumption can be achieved with the WuR:

$$\eta = \frac{O_{STA}+P_{WuRx}}{(P_{STA}\times FPP\times(1-O_{STA})} \quad (4)$$

II. Previous Related Research on Energy Efficiency Using Wake-Up radio

This section looks at the research works that had been done with the aim of improving energy efficiency of a WLAN transmission by integrating wake-up radio with its module considering; Channel Sensing, the WuR transmitter and Latency Reduction Techniques. Authors such as Suhua Tang *et al* [1, 2, 3, 5, 7, 8, 12, 33], M. Magno *et al* [4, 11, 14, 23], C. Petrioli *et al* [6, 14, 21] among others have done researches in this area revealing gaps that could be improved upon as they progress.

A. Channel Sensing

Though earlier implementation of the wake-up radio technology was with wireless sensor networks (WSN) [14, 13, 12] and much research is still on-going in that aspect [10, 11, 20, 21, 23,], attention has also shifted considerably to the use of these WuRs to reducing energy consumption of WLAN modules as seen in [1, 2, 5, 19, 12] by allowing the WuR to do the work of carrier sense for a WLAN module adopting pure asynchronous wake-up scheme [4, 12, 22] which allows the nodes to be in a deep-sleep mode until they are woken up using a low-power WuR [19]. Using the WuR to do channel sensing job for the WLAN module improves the energy consumption considerably but also presented challenges such as collision, latency, false wake-up, protocol overhead, traffic fluctuation which seriously affects sleep scheduling and balancing enhanced data rate and sensitivity with power consumption.

B. WLAN wake-up radio transmitter

While the traditional method requires that a separate wake-up transceiver (WuTx/WuRx) be installed on individual STA [12] in the network, [1, 15, 19, 22] contemplated the use of WLAN transceiver as a transmitter for the WuR thereby reducing complexity and cost and with further modification [19], energy consumption. J. Oller *et al* [19] proposed a novel WuR transmission system that enables any IEEE 802.11-enabled device to be used as a WuR transmitter without the need for hardware modification by using the subcarrier Modulation scheme as shown in Figure 4 to cause a high frequency 2.4GHz WLAN signal to emulate the low frequency 15KHz signal required by a WuRx.

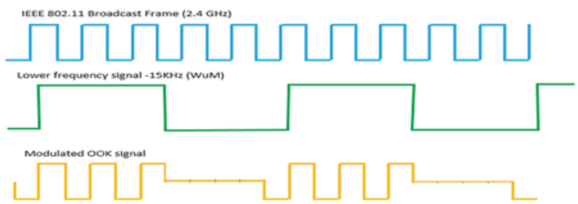

Figure 4: SubCarrier Modulation.

C. Collision

For the multiple STAs associated with an AP to be able to access the available channel for transmission of packets, they will all have to contend for it [1, 3, 5, 4, 22, 15], this contention must be done is such a way as to avoid collision which leads to latency and energy inefficiency [2, 18].

D. Latency Reduction

Latency result largely from collision where the network MAC protocol is not properly streamlined and this is the bases for the work in [5, 2, 3, 16, 26]. The impact of wake-up latency on the carrier sense mechanism was investigated by Suhua Tang *et al* in [2, 5] proposing backoff freezing (BOF) technique to help recover the carrier sense mechanism whenever a false wake-up occurs using CW to reduce the false wake-up probability as shown in Figure 9. With this method, the C_{BO} still continues to count down to negative within the wake-up period of its WLAN module, and should C_{BO} be greater than $-T_{WU}$ when the channel gets busy again, it is interpreted as C_{BO} being greater than 0 at the time of entering the wake-up period and also means that C_{BO} is falsely decreased by T_{WU} (Time taken for a WLAN module to wake up completely) and the WuR resets its C_{BO} to $C_{BO}+T_{WU}$, corresponding to the value of C_{BO} as at the time it entered the wake-up period. Should a WLAN module falsely wakes-up to find the channel busy, it retires to the sleep mode again thereby addressing false wake up, reduce latency that results therefrom and improve energy efficiency. The large CW however, results in creation of more idle-slots which translates to less spectral efficiency hence the trade-off between spectral efficiency and energy efficiency. Using the Bianchi's Markov model, the probability τ that a node transmits in a randomly chosen slot and the collision probability p under saturation scenario of a transmission were solved using the following equations:

$$\tau = \frac{2(1-2p)}{(1-2p)(W+1)+pW\left(1-(2p)^{M}\right)} \quad (5)$$

$$p = 1-(1-\tau)^{N-1}. \quad (6)$$

Then, the probability that a node is at the ith backoff stage with a backoff counter value k, is computed accordingly from τ and p.

III. Wake-up Radio Based Energy Efficiency Protocols

This section presents a tabulated quick-view of various techniques that had been proposed to solve the outlined issues with the WuR-WLAN merger in the effort to improve energy efficiency. It also discussed the techniques used of recent at tackling problems such as wake-up latency, CW adjustment for better collision avoidance and false wake-up among others. Some of the recent wake-up radio-based power saving protocols for WLAN include:

TABLE 1: SUMMARY OF ISSUES AND PROPOSED SOLUTIONS TO WuR BASED WLAN POWER SAVING PROTOCOLS

References	Problem addressed		Proposed Techniques
[1, 2, 3, 4, 7, 9, 19, 24, 25]	High power consumption due to continuous channel monitoring		WuR-CSMA, **Broadcast-based wake-up control framework, BOF, WuR-ESOC,** IEEE 802.11-based WuR system, CSMA/ECA **ECMA, (DirCorr(OCS),** Threshold Selection
[2, 3, 9, 17, 22]	Better CW adjustment		**WuR-CSMA,** CSMA/ECA, EDCF
[1, 4, 3, 25]	Collision		**WuR-CSMA, Broadcast-based wake-up control framework, ECMA,**
[1]	Relatively large Protocol overhead of wake-up per node		**Broadcast-based wake-up control framework**
[2]	False wake-up	Occurrence	CW Adjustment
[2]		Time	Early Sleep, negative C_{BO}
[2, 5]	Wake-up latency of WLAN module		**WuR-ESOC**, BOF,
[2]	Throughput		WuR-ESOC
[24]	Distortion impact of LPF on frame length detection		Threshold Selection
[7]	Reliability of Wake-up control		**DirCorr(OCS)**
[1]	Contention Initiation		**SNR/RSSI estimation,**

A. Wake-up Radio Based Carrier Sense Multiple Access (WuR-CSMA) [3]

Every WLAN Module is equipped with a low-power WuR operating on the same channel as the module. The system model of the WuR-WLAN node is shown in Figure 5

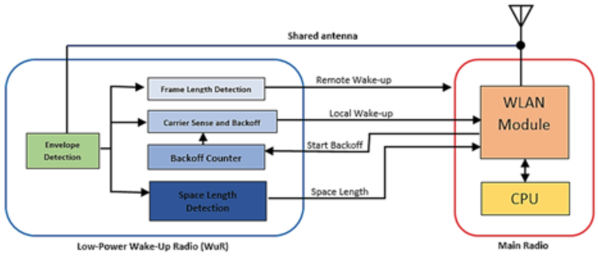

Figure 5: System model of the WuR-WLAN node

When the WLAN module has buffered data for **uplink** but the channel is occupied, the module sets a backoff value and also sets the backoff counter of the WuR to that value considering the current contention window (CW) established by the AP and then returns to sleep as illustrated in figure 6. The WuR sense the channel decreasing its backoff counter per idle slot but freezes it if channel is busy. The WLAN module is activated by the WuR as soon as the backoff counter reads zero.

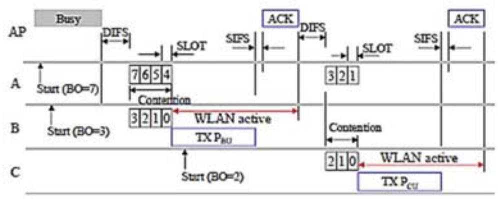

Fig. 6. An example of uplink transmissions in a WLAN consisting of an AP and three nodes A, B and C (from [3])

The WLAN module determines the contention value

$$CW_{min} \Leftarrow \begin{cases} CW_{min} + CW_{Delta} & if\ D < D_{min} \\ CW_{min} - CW_{Delta} & if\ D > D_{max} \end{cases}$$

D = average number of idle contention slots (lies between D_{min} and D_{max})

Limitation: Wake-up latency, high probability of collision as a result

B. Broadcast-based wake-up control Framework [1]

While [3] focused on uplink, this method emphasizes data downlink as seen in figure 7. The AP (a WLAN module but also serving as a WuR transmitter) broadcasts a wake-up message (WuM) carrying a TIM indicating the availability of packets, modulated unto its WLAN signal using the OOK modulation scheme. The WuR senses the channel and determines the availability of packets intended for its module by measuring RSSI/SNR on receiving the WuM, it then extracts the TIM, determines the number of contending nodes and calculates its SNR threshold. The WuR initiates backoff counter if the normalized SNR exceeds the threshold and decreases it per idle slot. It wakes up its WLAN module as soon as its backoff counter reads zero. On waking up, the WLAN module performs carrier sense to ascertain that the channel is idle. If it is, it sends a clear-to send (CTS) message to the AP requesting downlink of buffered data. If the channel is busy, it returns to sleep (False wake-up). At receipt of CTS, AP sends the data to the node in a burst with SIFS between adjacent frames then clears the more-data flag signaling end of the data-send followed by a DIFS after which contention can recommence between remaining nodes interested in using the channel. Space of DIFS or longer decreases the number of contending nodes by 1 and updates the SNR threshold.

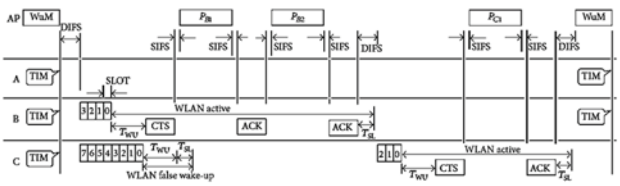

Figure 7: Wake-up control for the downlink transmission scheduling in a WLAN with an AP and 3 nodes (from [1])

The normalized SNR is calculated as:

$$Normalized\ SNR\ (\gamma_i) = \frac{absolute\ SNR\ (\gamma'_i)}{average\ SNR\ (\overline{\gamma'_i})}$$

$$\gamma_i = \frac{\gamma'_i}{\gamma'_t} \qquad (7)$$

$$f(\gamma) = \exp(-\gamma)\ and\ F(\gamma) = 1 - \exp(-\gamma) \qquad (8)$$

Limitation: False wake-up resulting from idle WLAN module wake-up period, Wake-up latency.

A. Backoff Freezing (BOF)[5]

This method allows the WuR to behave as though its backoff counter is frozen in the Wake-up period of a WLAN module thereby helping to recover the carrier sense mechanism and bring false wake up to a minimum. The innovation here is, when the Backoff Counter (C_{BO}) of a STA gets to zero and wakes up its WLAN module within the wake-up period of another module, it continues to decrement into negatives. Should the channel become busy before its WLAN module becomes fully awake, it resets its C_{BO} to **1+ N_{WU}** (where N_{WU} = Wake-up period in terms of slots) while the WLAN module goes into sleep mode. This process is called Backoff Freezing (BOF).

Limitation: The falsely awoken WLAN Module wakes up fully first before being returned to sleep mode, and this contributes significantly to energy consumption.

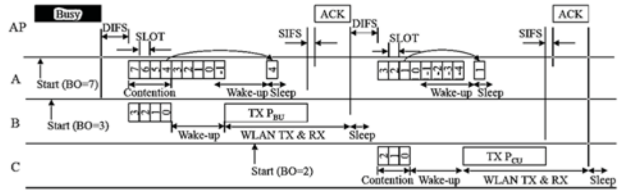

Figure 8: Backoff Freezing (from [5])

D. WuR-ESOC [2]

The goal of this technique, beyond energy efficiency was also to address the challenge of reducing false wake-up time/event resulting from the sensed idleness within the WLAN module's wake-up period as revealed in [1, 3, 5] and figure 9.

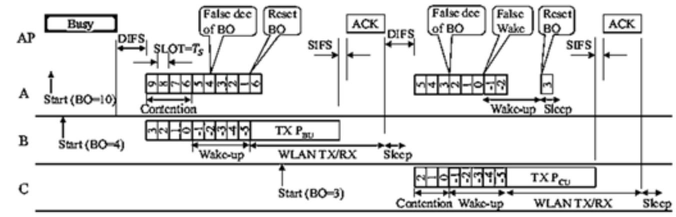

Figure 9: Resetting Backoff counters of falsely activated Nodes (from [2])

With this technique, a falsely awoken node is quickly put back to sleep **before** it becomes active thereby reducing false wake-up time.

Limitation: To completely eliminate false wake-up event between any two nodes, say A and B:

$$C_{BO}(A) + C_{BO}(B) > N_{WU} \qquad (9)$$

This can only be realized with large CW which will in turn degrade the spectral efficiency

IV. OPEN AREAS

The wake-up radio-based energy efficiency approach has considerably reduced the energy consumption of WLAN modules. However, the contention window approach created a tradeoff between energy and spectral efficiency. Increasing the size of the contention window reduces the probability of collision (increased energy efficiency) but also use-up more bandwidth (less throughput) as revealed in [2, 17, 22]. There also exists a tradeoff between the simplicity of the WuRx and the reliability of a WuR-based WLAN system. The wake-up radio receiver needs to be simple enough to run on very low-power but this simplicity of the WuR can also result in channel interference and increased false-wake up probability addressed in [2]. These compromises call for protocols that will helps achieve better tradeoff between these parameters.

V. CONCLUSION

This review takes a look at the efforts made in recent times at reducing the energy consumption of WLAN module and other related issues associated with using wake-up radio. It also identified research gaps that requires addressing with a more proficient approach. Obviously, the potential for wake-up radio to reduce energy efficiency of WLAN devices has been demonstrated and offers motivation for future wor

REFERENCES

[1] S. Tang and S. Obana, "Energy Efficient Downlink Transmission in Wireless LANs by Using Low-Power Wake-Up Radio," *Wirel. Commun. Mob. Comput.*, vol. 2017, no. ii, pp. 1–12, 2017.

[2] S. Tang and S. Obana, "Reducing false wake-up in contention-based wake-up control of wireless LANs," *Wirel. Networks*, vol. 0123456789, pp. 1–17, 2018.

[3] S. Tang, C. Zhang, H. Yomo, and S. Obana, "Energy and spectrum efficient wireless LAN by tightly integrating low-power wake-up radio," *IEEE Int. Symp. Pers. Indoor Mob. Radio Commun. PIMRC*, no. i, pp. 1–6, 2016.

[4] M. Magno and L. Benini, "An ultra-low power high sensitivity wake-up radio receiver with addressing capability," *Int. Conf. Wirel. Mob. Comput. Netw. Commun.*, pp. 92–99, 2014.

[5] S. Tang and S. Obana, "Tight integration of wake-up radio in wireless LANs and the impact of wake-up latency," *2016 IEEE Glob. Commun. Conf. GLOBECOM 2016 - Proc.*, 2016.

[6] C. Petrioli, D. Spenza, P. Tommasino, and A. Trifiletti, "A novel wake-up receiver with addressing capability for wireless sensor nodes," *Proc. - IEEE Int. Conf. Distrib. Comput. Sens. Syst. DCOSS 2014*, pp. 18–25, 2014.

[7] S. Tang, H. Yomo, and Y. Takeuchi, "Optimization of frame length modulation-based wake-up control for green WLANs," *IEEE Trans. Veh. Technol.*, vol. 64, no. 2, pp. 768–780, 2015.

[8] S. Tang and Z. Liu, "Radio-on-Demand Wireless LAN," *Encycl. Wirel. Networks*, pp. 1–4, 2019.

[9] J. Barcelo, B. Bellalta, C. Cano, A. Sfairopoulou, and M. Oliver, "Dynamic parameter adjustment in CSMA/ECA," *Lect. Notes Comput. Sci. (including Subser. Lect. Notes Artif. Intell. Lect. Notes Bioinformatics)*, vol. 6235 LNCS, pp. 13–24, 2010.

[10] D. Ghose, V. Pla, and F. Y. Li, "MAC Protocols for Wake-Up Radio: Principles, Modeling and Performance Analysis," *IEEE Trans. Ind. Informatics*, vol. 14, no. 5, pp. 2294–2306, 2018.

[11] M. Magno, V. Jelicic, B. Srbinovski, V. Bilas, E. Popovici, and L. Benini, "Design, Implementation, and Performance Evaluation of a Flexible Low-Latency Nanowatt Wake-Up Radio Receiver," *IEEE Trans. Ind. Informatics*, vol. 12, no. 2, pp. 633–644, 2016.

[12] S. Tang, H. Yomo, Y. Kondo, and S. Obana, "Wake-up receiver for radio-on-demand wireless LANs," *Eurasip J. Wirel. Commun. Netw.*, vol. 2012, 2012.

[13] L. Chen *et al.*, "Range extension of passive wake-up radio systems through energy harvesting," *IEEE Int. Conf. Commun.*, pp. 1549–1554, 2013.

[14] D. Spenza, M. Magno, S. Basagni, L. Benini, M. Paoli, and C. Petrioli, "Beyond duty cycling: Wake-up radio with selective awakenings for long-lived wireless sensing systems," *Proc. - IEEE INFOCOM*, vol. 26, pp. 522–530, 2015.

[15] Y. Kondo *et al.*, "Energy-efficient WLAN with on-demand AP wake-up using IEEE 802.11 frame length modulation," *Comput. Commun.*, vol. 35, no. 14, pp. 1725–1735, 2012.

[16] S. Chen, R. Ma, H. H. Chen, and W. Meng, "A segmented packet collision model for smart utility networks under WLAN interferences," *IEEE Trans. Wirel. Commun.*, vol. 15, no. 5, pp. 3506–3517, 2016.

[17] Sunghyun Choi, J. del Prado, Sai Shankar N, and S. Mangold, "IEEE 802.11 e contention-based channel access (EDCF) performance evaluation," pp. 1151–1156, 2004.

[18] L. Sanabria-Russo and B. Bellalta, "Traffic differentiation in dense collision-free WLANs using CSMA/ECA," *Ad Hoc Networks*, vol. 75–76, pp. 33–51, 2018.

[19] J. Oller *et al.*, "IEEE 802.11-enabled wake-up radio system: Design and performance evaluation," *Electron. Lett.*, vol. 50, no. 20, pp. 1484–1486, 2014.

[20] L. Guntupalli, D. Ghose, F. Y. Li, and M. Gidlund, "Energy Efficient Consecutive Packet Transmissions in Receiver-Initiated Wake-Up Radio Enabled WSNs," *IEEE Sens. J.*, vol. 18, no. 11, pp. 4733–4745, 2018.

[21] S. Basagni, C. Petrioli, and D. Spenza, "CTP-WUR: The collection tree protocol in wake-up radio WSNs for critical applications," *2016 Int. Conf. Comput. Netw. Commun. ICNC 2016*, pp. 0–5, 2016.

[22] I. Dcf and A. Control, "Contention Window Optimization for," vol. 7, no. 12, pp. 0–6, 2008.

[23] A. Pegatoquet, T. N. Le, and M. Magno, "A Wake-Up Radio-Based MAC Protocol for Autonomous Wireless Sensor Networks," *IEEE/ACM Trans. Netw.*, vol. 27, no. 1, pp. 56–70, 2019.

[24] S. Tang, H. Yomo, and S. Obana, "Dynamic threshold selection for frame Length-Based Wake-Up control," *IEEE Wirel. Commun. Lett.*, vol. 4, no. 6, pp. 609–612, 2015.

[25] M. F. Tuysuz, "Towards providing optimal energy-efficiency and throughput for IEEE 802.11 WLANs," *Int. J. Commun. Syst.*, 2018.

[26] R. Hamamoto, C. Takano, H. Obata, and K. Ishida, "Improvement of throughput prediction scheme considering terminal distribution in multi-rate WLAN considering both CSMA/CA and frame collision," *IEICE Trans. Inf. Syst.*, vol. E99D, no. 12, pp. 2923–2933, 2016.

[27] X. Zhang and K. G. Shin, "E-MiLi: Energy-Minimizing Idle Listening in Wireless Networks," *IEEE Trans. Mob. Comput.*, 2012.

[28] H. Yang, D. J. Deng, and K. C. Chen, "On energy saving in IEEE 802.11ax," *IEEE Access*, vol. 6, pp. 47546–47556, 2018.

[29] M. A. Santos, J. Villalón, and L. Orozco-Barbosa, "A novel QoE-aware multicast mechanism for video communications over IEEE 802.11 WLANs," *IEEE J. Sel. Areas Commun.*, vol. 30, no. 7, pp. 1205–1214, 2012.

[30] L. A. N. Man, S. Committee, and I. Computer, "Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications IEEE Computer Society Specific Requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications," vol. 2016, 2016.

[31] R. Palacios, G. Mengistie, J. Alonso-zarate, D. Kliazovich, and F. Granelli, "Analysis of an Energy-Efficient MAC Protocol Based on Polling for IEEE 802. 11 WLANs," 2014.

[32] D. C. Daly, S. Member, A. P. Chandrakasan, and A. Abstract, "An Energy-Efficient OOK Transceiver for Wireless Sensor Networks," vol. 42, no. 5, pp. 1003–1011, 2007.

[33] R. Piyare, A. L. Murphy, C. Kiraly, P. Tosato, and D. Brunelli, "Ultra Low Power Wake-Up Radios: A Hardware and Networking Survey," *IEEE Commun. Surv. Tutorials*, vol. 19, no. 4, pp. 2117–2157, 2017.

[34] A. A. Syed, M. O. Khan, J. Heidemann, J. Wills, and W. Ye, "Demo Abstract: A Sensornet-inspired Underwater Acoustic Modem for Wake-up and Data," 2008