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RESEARCH ARTICLE

Opportunistic Backscatter Communication Protocol Underlying Energy Harvesting IoT Networks

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ABSTRACT Traditional WiFi devices, wireless energy harvesting devices, sensor-driven smart gadgets, and backscatter communication tags can all be part of a heterogeneous wireless network. In the Internet of Things (IoT), the recently developed backscatter communication technology allows for battery-free communication. However, when wireless energy transmissions coexist alongside wireless data transmissions, collisions and interference become more frequent. In this paper, we present a heterogeneous wireless energy harvesting IoT network using an Opportunistic Backscatter communication Medium access control (OBM) protocol. It allows the backscatter tags to communicate with the reader in an energy harvesting IoT network in a smooth manner. For contention and communication, the backscatter tags employ the radio frequency (RF) signals provided by the hybrid access point (HAP) to the energy-strapped wireless nodes. When the devices request the HAP for wireless energy harvesting, the reader stimulates the tags for contention and communication. To access the channel with fewer collisions, wireless devices and backscatter tags utilize different contention techniques. For backscatter communications, network throughput, and energy efficiency, we identified the transmission probability of devices and tags, energy harvesting, and data transmission probability of nodes. When compared to traditional methods, the proposed protocol improves network throughput performance and energy efficiency.

INDEX TERMS Internet of Things (IoT), wireless energy harvesting, medium access control (MAC), backscatter communications.

I. INTRODUCTION

Internet of things (IoT) provides a pragmatic network platform for the envisioned future of integrated sensor-driven devices [2]. It extends network connectivity to widely deployed communicating nodes. Its applications range from smart buildings, connected cars, and wearables to connected healthcare [3]. In order to connect various things, a collaborative network architecture is required for the extended connectivity of heterogeneous networks, i.e., interconnectivity of smart cities and environment monitoring [4]. The implementation and the integration of a scalable network of micro and macro IoT inter-connectivity is a very challenging issue [5]. Network nodes not only require appropriate scheduling for seamless network connectivity but also continuous energy supply to efficiently perform their operations [6], [7].

Wireless energy harvesting network is a sustainable solution to the energy constrained conventional wireless sensors network [8]. Coexisting of wireless data transmission and radio frequency (RF) energy harvesting gives a sustainable solution for heterogeneous IoT connectivity and continuous energy supply [9]. Wireless energy harvesting is utilized in various applications to powering the RFIDs and energy constrained wireless devices [10]. Backscatter communication devices could exploit the RF signals transmitted by the access point (AP) or other wireless devices for communication with the information reader [11]. However, a multiuser backscatter

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communication network could experience interference in the wireless data transmission due to the wireless energy transmission [12], [13]. Therefore, advanced system and circuit design is required to implement a coexisting network of wireless information and energy transmission and/or backscatter communications.

Chen et al. studied throughput maximization of backscatter tags by considering transceiver and transmission coefficient design [14]. Distance between a tag and the transceiver impacts the performance of an ambient backscatter communication system due to the amount of harvested energy [15]. Mishra et al. propose multi-tag backscattering to a multi-antenna reader communication system aiming to maximize the sum-throughput [16]. A backscatter communication network powered by a power beacon station (PBS) is studied in [17], where backscatter tags utilize the wireless power signal of the PBS for information transmission. The deployed wireless relays assist them in relaying the information to enhance the network throughput. Cooperative wireless energy transfer can enhance the operational lifetime of multi-hope networks [18]. Wang et al. proposed relay selection and the adaptive backscatter coefficient mechanism to optimize the time allocation [19]. Similarly, clustering approach can prolong the network lifetime if mobility approach is considered. Lee et. al proposed an extended hierarchical clustering method considering the harvesting for energy harvesting network to enhance network lifetime [20].

To support both wireless information transmission and RF energy harvesting in a network, a distinct scheduling mechanism is required to avoid collisions of wireless transmissions. Li et al. propose a hybrid ambient backscatter communication system based on the harvest-then-transmit protocol [21]. In this communication system, the transmission duration is divided into wireless energy harvesting, ambient backscatter communication and data transmission phases. Also, multiple tags send information to a reader, where the backscatter tag's information transmission is conditioned on a threshold aiming to minimize collision [22]. In the system, a tag is allowed to randomly choose a sub-frame and transmit information only when the received power signal is above a backscatter threshold level. Selective channel access methods for contention and communication enhance the network energy efficiency [23].

Furthermore, a high data rate backscatter communication system is studied to develop an RF backscatter communication system for medical implanted devices [24]. Kwan et al. use time division, power splitting and backscatter combination protocols for wireless sensor networks [25]. It targets to implement the coexisting of RF energy harvesting and backscatter communications to enhance network throughput. However, the channel capacity of a network is affected by the received signal due to path loss and channel fading [26]. Guo et al. proposed a cognitive backscatter communication system to support passive IoT transmissions [27]. In the system, backscatter tags utilize a sinusoidal carrier signal to transmit information assisting IoT devices.

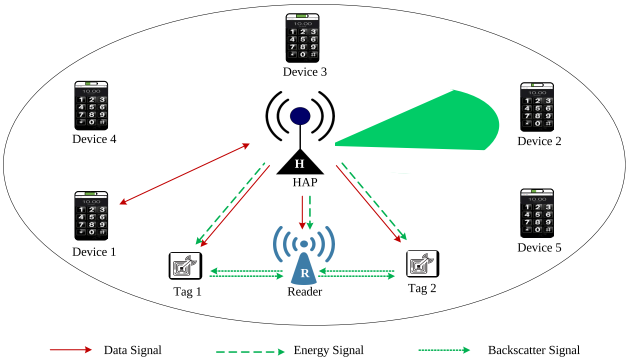

FIGURE 1. A coexisting network of backscatter communication and wireless energy harvesting network.

Zhang et al. presented a network stack to enable bit-by-bit communication in a heavily dynamic wireless energy harvesting conditions [28]. Hu et al. proposed access control mechanism for wireless powered devices by redesigning the superframe structuring by time switching strategy to improve network performance [29]. A multi-hope network is designed to increase the coverage area of wireless nodes. Ji et al. propose a multi-hop communication protocol for an energy harvesting network under the WiFi architecture [30]. The protocol allows the AP to send $CTS-to-self$ frame to reserve the channel and triggers the nodes to contend and to backscatter the RF signals using the harvested energy. A modified distributed coordination function (DCF)-based dominant channel occupancy (DCO) protocol is proposed [31]. The protocol lets the backscatter tags and wireless devices to contend for a shared channel. The backscatter tags use the RF signals of the WiFi helper to transmit information to the reader.

Ma et al. propose a distributed and demand-based (DDB) access mechanism for a diverse network of wireless devices and backscatter tags [32]. The protocol lets the AP to contend with wireless devices. As the AP succeeds, it transmits $CTS-to-self$ to suspend the transmission of wireless devices for backscatter communications. Then, it transmits a preamble to stimulate the tags for ambient backscattering and lets their contention begin. The backscatter tags then use WiFi signals to communicate with the AP. Cao et al. propose a distributed MAC protocol for backscatter communications based on ambient RF energy harvesting [33]. The protocol combines analogue channel sensing strategy with backoff mechanism for transmitting and receiving data, and harvesting energy.

However, the conventional protocols require the suspension of wireless data transmission of devices while allowing backscatter transmissions in a heterogeneous wireless IoT network. Therefore, a new access control mechanism is required for coexisting of wireless powered communication and backscatter communications in a heterogeneous wireless IoT network. In this paper, we propose an Opportunistic Backscatter communication MAC (OBM) protocol for RF energy harvesting IoT networks. The backscatter tags opportunistically utilize wireless energy signal transmitted by HAP to transmit/receive information to/from the reader. The HAP consisting of a PB and an AP either provides devices with wireless energy on request or allows them to transmit data. The IoT devices contend to access the medium for harvesting RF energy or wireless information transmission.

Our core contributions are; (i) We propose an opportunistic backscatter communication access control mechanism to coordinate the backscatter transmissions with wireless energy harvesting IoT networks. In the network, the backscatter tags opportunistically utilize wireless energy signal to transmit information to the reader and receive information from the reader. (ii) We derive the transmission probability of wireless devices and backscatter tags. (iii) We identify the transmission collision and success of wireless devices and backscatter tags affected by the amount of harvested energy. We determine the number of possible opportunistic backscatter transmissions during the wireless energy harvesting phase. Then, we show the enhancement of the proposed scheme in terms of throughput and energy efficiency.

II. SYSTEM MODEL

A. NETWORK MODEL

We consider a backscatter communication network underlying a wireless powered IoT network. The network consists of wireless energy harvesting devices, an HAP (AP+PB), underlying backscatter reader and tags. The wireless energy harvesting devices communicate with the HAP and also harvest energy from the RF signals of the HAP, as shown in Fig. 1. The HAP transmits directional wireless power adaptively to the energy harvesting device [34]. The receives power of a device

$$P_n = P_B \eta h_n, \tag{1}$$

where P_B is the power transmitted by the HAP, η is the conversion efficiency, $h_n = \frac{|\tilde{h}_n|^2}{1+r_n^\alpha}$, where $\tilde{h}_n$ is small scale Rayleigh fading, r is the distance between a device and the HAP, and α is the path loss exponent [35]. The backscatter tags communicate with the reader utilizing the wireless energy signals transmitted by the HAP. The tags are allowed to communicate when the reader triggers them to contend for the shared channel. Similar to the wireless devices, the reader can decode the type of a packet transmitted by the wireless devices and the HAP to intercommunicate. An energy deficient node requests the HAP for RF energy signal to harvest energy. Then, the HAP transmits power signal with beamforming to focus the signal towards the desired wireless device.

B. BACKSCATTER COMMUNICATION

The backscatter tags communicate with the reader in two different links. A tag transmits information in the uplink to the reader and downlink is used by the reader to transmit information to a tag. It transmits information with the reader via a switching mechanism. The switching

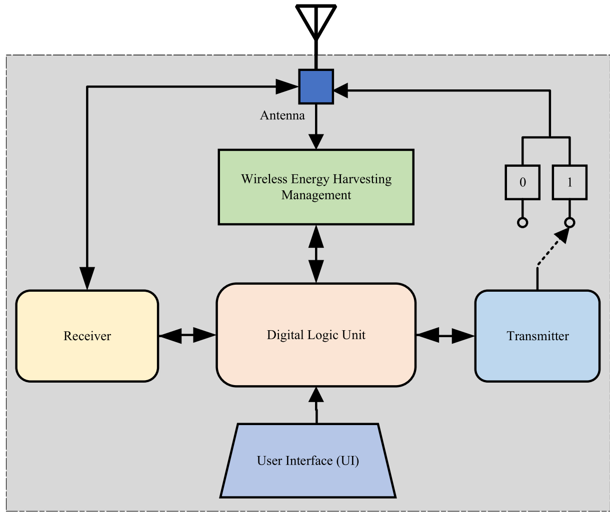

FIGURE 2. A backscatter tag architecture design representing the communication and RF energy harvesting management.

mechanism consists of two power states, reflecting and non-reflecting (absorbing) power states. The former state represents transmitting bit ‘1’ while the latter represents transmission of a bit ‘0’. A backscatter tag consists of an antenna, a digital logic unit (DLU), and an RF harvesting and power management unit, as illustrated in Fig. 2. The DLU interconnect the user interface and the transceiver. It is responsible to control the transmitter, which is used for managing the two power states, the reflecting and non-reflecting states. The management unit manages antenna to receive information or transmit information and to use it to harvest RF energy from the wireless power signal.

The information transmission of a backscatter tag may experience inadvertent interference from nearby tags. Therefore, it needs a coding scheme prior to transmission, i.e., FM0, to avoid unexpected interference from the nearby tags. The FM0 coding scheme modulates binary bits [36]. In FM0, symbol is transitioned for bit ‘0’ or bit ‘1’ and an additional mid-bit transition occurs for bit ‘0’, as depicted in Fig. 3. The backscatter communication is conditioned to the sensitivity of a tag. The sensitivity of a tag is called the minimum power required for tag to activate [37]. Currently, the minimum power required for a tag to activate if the received power is range $-20dBm \sim -10dBm$ [38]. This activation power is transmitted by the reader to the backscatter tag to activate them for communication using preamble. The frame format of a backscatter tag consists of a preamble and information bits as shown in Fig. 4. Preamble bits, also called exciting bits, are used to excite tags for contention and/or to detect the beginning of a frame. Information bits are used to exchange information to the receiver. This portion of the bits consists of a Header, Data and a cyclic redundancy check (CRC) fields. The Header field carries the information of a frame type i.e., Data or ACK and the Data field contains information to be delivered. The CRC field is used to check errors in the Header and the Data fields.

The reader excites the backscatter tags by sending a preamble to let them contend. The activation power is transmitted by the reader to the backscatter tag to activate them for communications. The reader excites or sensitize the tags by the preamble and minimum activation power required. The preamble is a sequence of alternating bits of ones and zeros used to wake up the tags. A backscatter tag modulates its transmitting signal with the RF energy signal transmitted by the HAP to send information to the reader. One of the most important parts of the communication is the decoding of a transmitted signal. A signal thresholding mechanism is used to detect the desired signal. The reader receives two signals simultaneously, the backscatter signal and the HAP's power signal which enables it to decode the transmitted signal.

The reader can decode the signal by comparing the backscatter signal and HAP's signal since both signals have different magnitudes. Therefore, a reader can conveniently separate the backscatter signal by subtracting it from that of the HAP. Different data rates of a backscatter tag and the HAP paves a way to better detect and sense the channel for the reader and a backscatter tag. Therefore, a backscatter signal can be conveniently distinguished from that of the HAP to extract information [39]. It can also detect the preamble of a frame to identify the beginning of a frame for communication. Similarly, it can get the information of the duration of the available channel for data communications from the received frame.

III. PROPOSED OPPORTUNISTIC MAC PROTOCOL

We propose an opportunistic backscatter communication MAC (OBM) protocol for a heterogeneous wireless IoT network. The protocol is for a backscatter network underlying an IoT network utilizing wireless power signals to communicate, as shown in Fig. 5. It provides a distributed channel accessing opportunities to backscatter tags coexisting with wireless devices in the network. The wireless devices and the backscatter tags contend to access the shared channel with their particular contention mechanisms. Particularly, the backscatter tags are excited to contend and communicate when the reader detects energy request packets of a wireless device. On the contrary, the wireless devices contend to access the channel either to harvest energy or to transmit data based on the energy availability.

The OBM protocol allows backscatter tags to opportunistically utilize the wireless power in a wireless energy harvesting environment. The overall mechanism can be briefly summarized as; (i) In a network, the wireless energy harvesting nodes contend to access channel in a distribution mechanism of exponential backoff contention and channel reservation handshaking mechanism to access channel for data communication and/or energy harvesting. (ii) After accessing the channel the devices choose to transmit data or/and harvest energy based on the battery threshold level. (ii) The wireless devices energy utilizing the wireless power transmitted by the HAP. (iii) The reader of the tags contents with wireless devices to access channel for the backscatter tags communication. it immediately invokes the tags by a preamble to content for backscatter communication. (iv) The backscatter tags use the backoff contention mechanism to access channel and backscatter the wireless energy signal of the HAP.

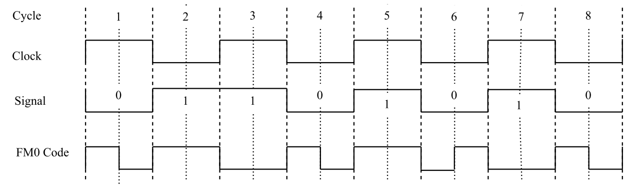

FIGURE 3. An example of FM0 coding used by a tag to avoid transmission interference from nearby tags.

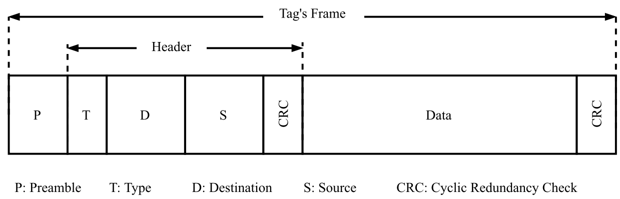

FIGURE 4. An example of a frame format used by a backscatter tag to communicate.

A. HARVESTING DEVICES ACCESS CONTROL

Wireless devices utilize the harvested RF energy from the wireless power signal transmitted by the HAP to transmit information. The wireless devices contend to access the channel prior to the information transmission or energy harvesting. The channel is accessed using a binary exponential backoff (BEB) contention mechanism. Initially, each device selects a random value in the backoff window $[0, W_j - 1]$ and initial backoff stage i.e., $W_0 = W_{min}$ and $j = 0$. The backoff window W_j is increased backoff stage j on each collision, i.e., $W_j = 2^j W_{min}$ and $0 \leq j \leq m$, until it attains the maximum backoff window W_{max} at the backoff stage m, i.e., $W_{max} = 2^m W_{min}$.

The backoff counter value is decreased by one at each idle slot till it becomes zero. Conversely, a device halts its counter when it senses an ongoing transmission of a nearby device. When the counter reaches zero, a wireless device transmits a frame to the HAP to reserve the channel. The transmission could reach successfully to the HAP or it might result in collision. The outcome of the transmission succeeds when only a single device transmits a frame. Conversely, the transmission results in collision when two or more devices simultaneously transmit their frames.

The devices require to reserve the channel before transmitting information or harvesting energy. For this purpose, the channel is reserved by a two-way handshaking mechanism. An example of the handshaking mechanism is given in Fig. 5. For example, after succeeding in contention, the Device1 transmits a request to send (RTS) frame to the HAP. As a channel clearance response, the HAP transmits a clear to send (CTS) frame after short inter frame space (SIFS). Next,

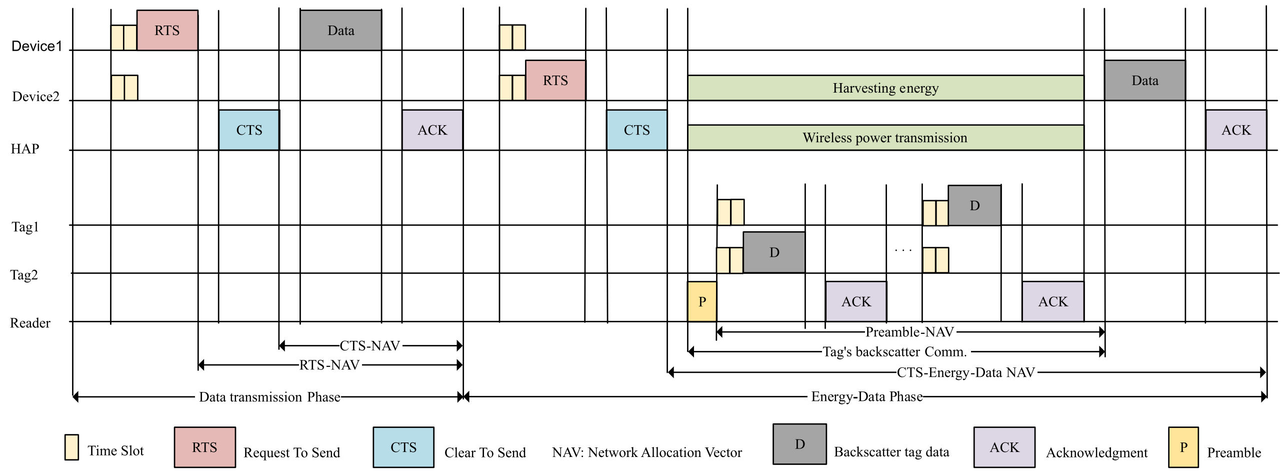

FIGURE 5. An example of the proposed protocol enabling the wireless powered IoT communication and the backscatter communication in a heterogeneous IoT network.

the Device1 waits for SIFS prior to transmit data to the HAP. As a feedback response to the received frame, The HAP transmits an acknowledgment (ACK) to the Device1. Then, the Device2 which needs energy transmits an RTS frame to reserve the channel for harvesting energy. The HAP transmits a CTS frame after an SIFS to the Device2. It transmits wireless energy signal after SIFS to the Device2. Subsequently, the device waits for SIFS and transmits data to the HAP when it is required to transmit. Thus, it can get the benefits of the accessed channel more efficiently. Then, the HAP acknowledges the received data by transmitting an ACK frame to the Device2. Then, the wireless devices wait an interval equals to distributed inter-frame space (DIFS) to continue their contention again.

B. OPPORTUNISTIC BACKSCATTER ACCESS CONTROL

The backscatter tags communicate with the reader when they are triggered to contend for the channel. The reader listens to the transmission of wireless devices in the shared channel. It listens to the channel to detect the HAP's energy signal to the wireless devices. After detecting the energy request/response frame (RTS/CTS) of the wireless devices, it transmits a preamble, to tags. The transfer of energy signals to a wireless device by the HAP creates an opportunity for backscatter tags to communicate. The backscatter tags use the wireless power signals of the HAP to contend and backscatter the wireless energy signal to the reader.

A wireless energy harvesting device transmits an RTS frame to the HAP asking for energy when it requires to harvest energy. In return, the HAP transmits a CTS frame to inform the devices about the availability of the channel for harvesting energy. The reader reads the transmitted CTS frame and transmits a preamble to activate the backscatter tags for contention and communication. The preamble signal indicates the availability of the channel and the beginning of backscatter transmission.

The backscatter tags communicate with the reader using a reflection or non-reflection mechanism carried by a low power circuitry. A low power circuit for backscatter tags perform carrier sensing and packet decoding [39]. The energy detection process is carried by a two-stage mechanism, i.e., an envelope and a threshold mechanism. The envelope stage is done by resistor-capacitor (RC) circuit and a detector used to filter out the required signals and average out randomness of the detected signals. The RC circuit is used as a filter to allow the desired frequencies and block the others. The threshold stage is done by RC circuit and a comparator. It develops a threshold signal to compare it with the received signal and extract the transmitted information. The reader also uses the same thresholding mechanism to decode the transmitted information. Conversely, the wireless devices perform carrier sensing by using the conventionally used energy detection mechanism.

The backscatter tags begin their contention when the HAP transmits energy signal to the wireless device in association with the devices' energy requirements. The backscatter tags use binary exponential backoff (BEB) contention mechanism for accessing the channel. Initially, tags select random value in backoff window $[0, W_{min} - 1]$ and decreases the counter by a one after a slot of length σ when channel is sensed idle until it equals zero. Conversely, it freezes the counter value when the channel is used by other device. After receiving the preamble, the tags begin decreasing the value of the backoff window until it equals zero. For example, the Tag2 succeeds in contention and transmits a data frame to the reader (see Fig. 5). The HAP confirms the reception of the data by sending an *ACK* frame to the Tag2 after *SIFS*. Next, when the Tag1 succeeds in contention, it transmits a data frame to the reader. In return, it receives an *ACK* frame from the reader after *SIFS* confirming the reception of the transmitted frame.

However, the backoff window is doubled by a tag when its backscattered transmission collides with other tags' transmissions. The transmission by the tags is required to be limited within the allowed transmission duration. Therefore, the tags need to identify the communication duration before a transmission begins. The transmission of the backscatter tags during the ongoing energy transmission needs to end before the specified time.

The proposed scheme provides an access control method for coexisting network of backscatter communication and wireless energy harvesting network. The backscatter tags opportunistically the wireless transmission of wireless energy harvesting nodes to communicate the reader. It enhances the network throughput and energy efficiency of wireless communication network. The newly emerged zero-power communication or ultra-power consumption is used to achieve massive interconnection and large scale coverage enabled by wireless energy harvesting and backscatter communication [39]. The application with zero-power consumption of wireless energy harvesting and backscatter communication are widely distributed in logistic and warehousing, smart homes, smart wearable, medical health [39], [43].

There are certain limitation of the coexisting of backscatter and wireless energy harvesting communication network which are opened to work on. First, the power of wireless signal fades with the increase of distance of nodes form power transmitter which enforces more time to harvest energy. Second, the backscatter tags may need more duration for contention and communication which can delay the transmission of wireless nodes. Third, the increase of backscatter tags would increase the probability of collision of packets which can decrease the tags throughput. Fourth, the contention of data transmission and energy harvesting nodes occurs simultaneously which can adversely affect the access of energy starved nodes. The challenges are open to focus on to achieve zero-power consumption networks.

IV. PERFORMANCE ANALYSIS

The wireless energy harvesting devices and the backscatter tags contend to access channel by employing a specific contention mechanism. The devices either choose to harvest energy or transmit data based on the available energy. Information is transmitted utilizing the harvested energy.

A. WIRELESS DEVICE TRANSMISSION

A device's behavior is modeled by a two-dimensional Markov chain for its binary exponential backoff mechanism to access the channel [40]. Let the bidiemensional Markov chain is represented by $\{c(t), s(t)\}$ where $c(t)$ and $s(t)$ represent the backoff time counter and backoff stage respectively [40]. The transition probabilities are

$$\begin{aligned} P\{j,l|j-1,0\} &= \frac{p}{W_j}, \quad 0 \le l \le W_j - 1,\ 1 \le j \le m \\ P\{0,l|j,0\} &= \frac{(1-p)}{W_0}, \quad 0 \le l \le W_0 - 1,\ 0 \le j \le m \\ P\{m,l|m,0\} &= \frac{p}{W_m}, \quad 0 \le l \le W_m - 1 \\ P\{j,l|j,l+1\} &= 1, \quad 0 \le l \le W_i - 2, 0 \le j \le m, \end{aligned} \tag{2}$$

where p is the conditional collision probability.

Let the stationary probability of the bi-dimensional Markov chain be $b_{j,l} = \lim_{t\to\infty} P\{c(t) = l, s(t) = j\}$ which gives the balance equation,

$$b_{j-1,0}.p = x_{j,0}. \tag{3}$$

Now the distribution of state j can be expressed as,

$$b_{j,0} = p^j b_{0,0}, \quad 0 < j < m. \tag{4}$$

And, when backoff stage is m then

$$b_{m-1,0}.p = (1-p)b_{m,0}, \tag{5}$$

which gives

$$b_{m,0} = \frac{p^m}{1-p} b_{0,0}. \tag{6}$$

For $l \in (1, W_j - 1)$ and j,

$$b_{j,l} = \frac{W_j - l}{W_j} b_{j,0} \quad j \in (0, m), \quad l \in (0, W_j - 1), \tag{7}$$

where

$$b_{j,0} = \begin{cases} (1-p).\sum_{k=0}^{m} b_{k,0} & j = 0 \\ p.b_{j-1,0} & 0 < j < m \\ p.(b_{m-1,0} + b_{m,0}) & j = m \end{cases}. \tag{8}$$

which gives

$$\sum_{j=0}^{m} b_{j,0} = \frac{b_{0,0}}{(1-p)}. \tag{9}$$

Now, the summation of the probabilities of the Markov chain at saturated states are expressed as,

$$\begin{aligned} 1 &= \sum_{j=0}^{m}\sum_{l=0}^{W_j-1} b_{j,l} = \sum_{j=0}^{m} b_{j,0} \sum_{l=0}^{W_j-1} \frac{W_j - l}{W_j}, \\ &= \sum_{j=0}^{m} b_{j,0} \frac{W_j + 1}{2} = \sum_{j=0}^{m} b_{j,0} \frac{2^j W + 1}{2}. \end{aligned} \tag{10}$$

which can be rewritten as,

$$\begin{aligned} 1 &= \frac{W}{2}\sum_{j=0}^{m} b_{j,0}.2^j + \frac{1}{2}\sum_{j=0}^{m} b_{j,0}, \\ &= \frac{W}{2}(\sum_{j=0}^{m-1} b_{j,0}.2^j + b_{m,0}.2^m) + \frac{1}{2}\sum_{j=0}^{m} b_{j,0}. \end{aligned} \tag{11}$$

From (4), (6) and (9) we can rewrite (11) as,

$$\begin{aligned} 1 &= \frac{W}{2}(\sum_{j=0}^{m-1} 2^j p^j.b_{0,0} + \frac{2^m p^m}{(1-p)} b_{0,0}) + \frac{1}{2}\frac{b_{0,0}}{(1-p)}, \\ &= \frac{b_{0,0}}{2}[W.(\sum_{j=0}^{m-1}(2p)^j + \frac{(2p)^m}{(1-p)}) + \frac{1}{(1-p)}], \\ &= \frac{b_{0,0}}{2} \frac{W.(\sum_{j=0}^{m-1}(2p)^j(1-p) + (2p)^m)}{(1-p)} + \frac{1}{(1-p)}], \end{aligned}$$

$$= \frac{b_{0,0}}{2} \frac{W.(\sum_{j=0}^{m-1}(2p)^j - p\sum_{j=0}^{m-1}(2p)^j + (2p)^m) + 1}{(1-p)},$$
$$= \frac{b_{0,0}}{2} \frac{W.(1 + p\sum_{j=0}^{m}(2p)^j) + 1}{(1-p)},$$
$$= \frac{b_{0,0}}{2} \frac{W + pW\frac{(1-(2p)^m)}{(1-2p)} + 1}{(1-p)}, \tag{12}$$

which gives

$$b_{0,0} = \frac{2(1-2p)(1-p)}{(W+1)(1-2p) + pW(1-(2p)^m)}. \tag{13}$$

A device's stationary probability of transmission ψ is derived as

$$\psi = \sum_{i=0}^{m} b_{i,0} = \frac{(2-4p)}{(1-2p)\mathcal{W} + pW_{min}(1-(2p)^m)}, \tag{14}$$

where $\mathcal{W} = W_{min} + 1$ and the stationary conditional collision probability

$$p = 1 - (1-\psi)^{n-1}, \tag{15}$$

where n is the number of wireless devices. The transmission probability with conditional collision probability p can be rewritten as

$$\psi(p) = \frac{2}{\mathcal{W} + pW_{min}\sum_{j=0}^{m-1}(2p)^j)}. \tag{16}$$

Then, p can be rearranged to find the stationary transmission probability

$$\psi = 1 - \left(\sqrt[n-1]{1-p}\right). \tag{17}$$

The probability that at least one device transmits a frame is

$$p_{tr} = 1 - (1-\psi)^n. \tag{18}$$

The devices sense the channel at each slot and attempt to transmit data when the channel is available. The probability that no device transmit in a slot is

$$p_{idle} = 1 - p_{tr} = (1-\psi)^n. \tag{19}$$

Similarly, we can find the device's success transmission probability

$$p_{succ} = \frac{n \cdot \psi(1-\psi)^{n-1}}{p_{tr}} = \frac{n \cdot \psi(1-\psi)^{n-1}}{1-(1-\psi)^n}. \tag{20}$$

The probability of collision can be identified as

$$p_{col} = p_{tr} - p_{suc},$$
$$= 1 - (1-\psi)^n - \frac{n \cdot \psi(1-\psi)^{n-1}}{1-(1-\psi)^n}. \tag{21}$$

B. ENERGY HARVESTING AND DATA TRANSMISSION

Let energy harvesting nodes be randomly distributed on the disc D with the radius R. The HAP is located at the center which transmits power to the wireless energy harvesting nodes. The spatial density of point G for node is [35]

$$f_G(g) = \frac{1}{\pi R^2}. \tag{22}$$

The channel gain is represented as a random variable h_n with independent and identical distribution (i.i.d.) properties. Its cumulative distribution function (CDF) is derived as [41]

$$F_{h_n}(h) = P(h_n \leq h),$$
$$= \int_0^{2\pi}\int_0^{R}\left(1 - e^{-(1+r^\alpha)u}\right)\frac{1}{\pi R^2} r dr d\theta,$$
$$= \int_0^{R}\left(1 - e^{-(1+r^\alpha)h}\right)\frac{2r}{R^2} dr. \tag{23}$$

Considering the free space wireless communication environment, we assume that the path loss $\alpha = 2$. The CDF of the random channel is derived as

$$F_{h_n}(h) = \int_0^{R}\left(1 - e^{-(1+r^2)h}\right)\frac{2r}{R^2} dr,$$
$$= 1 - \frac{e^{-h}}{R^2 h} + \frac{e^{-(1+R^2)u}}{R^2 h},$$
$$= \frac{R^2 h - e^{-h} + e^{-(1+R^2)h}}{R^2 h}, \tag{24}$$

and its PDF is derived as,

$$f_{h_n}(h) = \frac{(1+h)e^{-h} - \left(1 + (1+R^2)h\right)e^{-(1+R^2)h}}{R^2 h^2}. \tag{25}$$

The expected amount of harvested energy by the spatially distributed nodes can be calculated as

$$\mathbb{E}[E_n]$$
$$= \int_0^{\infty} P_B \eta T_{har} h f_{h_n}(h) dh,$$
$$= \lim_{y\to\infty}\int_0^{y} \frac{(1+h)e^{-h} - (1+(1+R^2)h)e^{-(1+R^2)h}}{R^2 h^2} \mathcal{C} h dh,$$
$$= \frac{\mathcal{C}}{R^2 h}\lim_{y\to\infty}\int_0^{y} (1+h)e^{-h}$$
$$- (1+(1+R^2)h)e^{-(1+R^2)h} dh. \tag{26}$$

where $\mathcal{C} = P_B \eta T_{har}$. Then, Eq. (26) can be rearranged as,

$$\mathbb{E}[E_n] = \frac{\mathcal{C}}{R^2}\lim_{y\to\infty}\left(\int_0^{y}\left(e^{-a_1 h} - (1+R^2)e^{-(1+R^2)h}\right)dh + \int_0^{y}\left(\frac{e^{-a_1 h} - e^{-(1+R^2)h}}{h}\right)dh\right),$$

$$= \frac{\mathcal{C}}{R^2} \lim_{y\to\infty} \int_0^y \Big(\frac{e^{-a_1 h} - e^{-(1+R^2)h}}{h} \Big) dh,$$
$$= \frac{\mathcal{C}\ln((1+R^2))}{R^2} = \frac{P_B \eta \overline{T}_{hr} \ln(1+R^2)}{R^2}, \quad (27)$$

where $\lim_{y\to\infty} \int_0^y (e^{-a_1 h} - e^{-(1+R^2)h})/h)dh = \ln(\frac{(1+R^2)}{a_1})$, $\lim_{y\to\infty} \int_0^x (e^{-a_1 h} - (1+R^2)e^{-(1+R^2)h})du = 0$, and $a_1 = 1$ [41].

Devices harvest energy from the RF signal transmitted by the HAP. The expected amount of harvested energy by a node can be calculated as

$$E_{har} = \mathbb{E}[E_n] p_{succ}, \quad (28)$$

where T_{har} is the duration of harvesting energy. Energy consumption could occur either in a successful frame transmission or collision of transmissions. It varies depending the duration of the frame transmission. The energy utilized during the collision of frames

$$E_{col} = P_n T_{RTS}, \quad (29)$$

where T_{RTS} is the duration of the RTS frame.

The energy consumption when a transmission succeeds is calculated as

$$E_{succ} = P_n \cdot T_{suc}, \quad (30)$$

where T_{suc} is the duration of a successful transmission,

$$T_{suc} = T_{RTS} + T_{CTS} + T_H + T_P + T_{ACK}. \quad (31)$$

The time intervals T_{CTS}, T_H, T_P, and T_{ACK} are the transmission time of the CTS frame, the packet header H, and payload P, and the acknowledgment frame ACK, respectively. The total energy utilized in either successful data transmission or collided transmission

$$E_{con} = E_{succ} p_{succ} + E_{col} p_{col}. \quad (32)$$

Energy is also consumed in transmitting the RTS frame when a device chooses to harvest energy. The expected amount of energy consumption in the channel access for harvesting energy is

$$E_{c,h} = E_{succ} p_{succ}. \quad (33)$$

Therefore, the net-amount of harvested energy during the harvesting phase is

$$E_h = E_{har} - E_{succ} p_{succ}. \quad (34)$$

Now, the stationary probability of harvesting energy of a device

$$p_{har} = \frac{E_{con}}{E_{con} + E_h}. \quad (35)$$

And the stationary probability of transmitting data is

$$p_{data} = 1 - p_{har}. \quad (36)$$

TABLE 1. System parameters.

Parameter	Value
Payload size	8,184 bits
PHY header size	128 bits
Tags' remaining time (T_f)	450 μs
MAC header size	272 bits
Conversion efficiency (η)	0.8
RTS frame size	288 bits
Min. backoff window (W_{min})	32
CTS frame size	240 bits
Max. backoff stage (m)	3
ACK frame size	240 bits
Energy threshold	0.5
Data rate	1 Mbit/s
Frame size for backscatter tag	400 bits
DIFS	128 μs
Transmission power (P_B)	4 $\sim$ 10 W
SIFS	28 μs
Harvesting time (T_{har})	8584 μs
Slot time (σ)	50 μs
Path loss exponent (α)	2
Preamble duration (T_{prm})	10 μs
Duration for backscatter tag	400 μs
Propagation delay	1 μs
Power consumption (P_n)	0.02 W
Devices distance (r)	2$\sim$ 10 m

C. BACKSCATTER COMMUNICATION

The backscatter tag use BEB mechanism to access the channel when the reader excites them to contend. The backscatter communication occurs in the energy harvesting period of a wireless device. Since the backscatter tags opportunistically transmit data we assume that the backscatter tags holds the frames till the reception of preamble from the reader. We assume that tags have equal size of packet. The stationary transmission probability of tags is derived by a two dimensional Markov chain of the backoff stage and the backoff window as [40]

$$\zeta = \frac{(2-4q)}{(1-2q)\mathcal{W} + qW_{min}(1-(2q)^m)}, \quad (37)$$

where $\mathcal{W} = W_{min} + 1$ and q is the conditional collision probability. The conditional collision probability of tag is

$$q = 1 - (1-\zeta)^{b-1}, \quad (38)$$

where b is the number of tags. The transmission probability of backscatter tag can be rewritten as

$$\zeta(q) = \frac{2}{\mathcal{W} + qW_{min}\sum_{j=0}^{m-1}(2q)^j}. \quad (39)$$

The transmission probability is dependent on the size of the minimum backoff contention window W_{min} and the backoff stage m. When $m = 0$, the transmission probability of a backscatter tag becomes,

$$\zeta = \frac{(2-4q)}{(1-2q)\mathcal{W}} = \frac{2}{W_{min}+1}. \quad (40)$$

The distinct size of backoff contention window for wireless devices and backscatter tags would achieve distinct transmission probability.

Now, to find ζ we can rewrite (38) as

$$\zeta = 1 - \big(1-q\big)^{b-1}, \quad (41)$$

where b is the number of backscatter tags. Thus, Eqs. (37) and (41) gives us the value of q and ζ, respectively. The transmission probability of tag

$$q_{tr} = 1 - (1-\zeta)^b. \tag{42}$$

Now, we can find the probability of the idle slot for the backscatter transmission as

$$q_{idle} = 1 - q_{tr} = (1-\zeta)^b. \tag{43}$$

The success probability q_{succ} of a tag within the backscatter transmission is

$$q_{succ} = \frac{b\cdot\zeta(1-\zeta)^{b-1}}{p_{tr}} = \frac{b\cdot\zeta(1-\zeta)^{b-1}}{1-(1-\zeta)^b}. \tag{44}$$

Then, the collision probability of the backscatter transmissions can be identified as,

$$\begin{aligned} q_{col} &= q_{tr} - q_{suc}, \\ &= 1-(1-\zeta)^b - \frac{b\cdot\zeta(1-\zeta)^{b-1}}{1-(1-\zeta)^b}, \\ &= \frac{1-(1-\zeta)^{2b} - b\cdot\zeta(1-\zeta)^{b-1}}{1-(1-\zeta)^b}. \end{aligned} \tag{45}$$

D. THROUGHPUT AND ENERGY EFFICIENCY

The number of successful transmission bits over the average channel time is called device throughput. In the network, throughput could be achieved by the wireless devices, the backscatter tags or both.

1) DEVICE THROUGHPUT

Let S_D be the device-throughput of the device Then, it can be represented as

$$S_D = \frac{p_{tr}\cdot p_{suc}\cdot \mathbb{E}[P]}{(1-p_{tr})\sigma + p_{tr}(1-p_{suc})T_{col} + p_{tr}\cdot p_{suc}\cdot T_{ed}}. \tag{46}$$

where

$$T_{ed} = p_{har}T_h + p_{data}T_d, \tag{47}$$

and $\mathbb{E}[P]$ is the average payload size of a device. The duration of a device when it successfully transmits data,

$$T_d = T_{RTS} + T_{CTS} + T_H + T_P + T_{ACK} + 3SIFS + DIFS, \tag{48}$$

and the time interval when a device needs to harvest energy

$$T_h = T_{RTS} + T_e + T_H + T_P + T_{CTS} + T_{ACK} + 3SIFS + DIFS, \tag{49}$$

where T_e is the duration specified for harvesting energy. Similarly, we can calculate the time interval when transmissions collide

$$T_{col} = T_{RTS} + SIFS + DIFS. \tag{50}$$

2) BACKSCATTER THROUGHPUT

The number of bits transmitted by the backscatter tags in the average channel time is called backscatter throughput,

$$S_T = \frac{p_{tr}\cdot p_{suc}\cdot q_{tr}\cdot q_{suc}\cdot p_{har}\cdot \eth\cdot \mathbb{E}[P_T]}{(1-p_{tr})\sigma + p_{tr}(1-p_{suc})T_{col} + p_{tr}\cdot p_{suc}\cdot T_{ed}}, \tag{51}$$

where $\mathbb{E}[P_T]$ is the average payload size of a backscatter tag, and

$$\eth = \frac{T_{av}}{T_{ut}}, \tag{52}$$

where T_{av} is the available time for the backscatter tag transmissions, and T_{ut} is the time utilized by the tags for contention and data transmission. The available time for the backscatter tag is

$$T_{av} = T_{har} - T_{prm} - T_f, \tag{53}$$

where T_{prm} is the preamble time and T_f is the time interval between the end of the backscatter transmission and the end of energy harvesting. The time utilized in backscatter transmission

$$T_{ut} = q_{tr}\sigma + q_{tr}(1-q_{suc})T_c + q_{tr}q_{suc}T_s. \tag{54}$$

The time used in the tags' transmission collision is

$$T_c = T_{tag} + DIFS, \tag{55}$$

and the time used in the tag's transmission success is

$$T_s = T_{tag} + SIFS + T_{ACK} + DIFS, \tag{56}$$

where T_{tag} is the tag's packet transmission time.

3) NETWORK THROUGHPUT

The overall network throughput is the successful number of bits transmitted by the devices and the backscatter tags over the average channel time. Let S_N be the network throughput, then

$$\begin{aligned} S_N &= S_T + D_T, \\ &= \frac{p_{tr}\cdot p_{suc}\cdot\left[p_{har}\cdot q_{tr}\cdot q_{suc}\cdot \mathbb{E}[P_T] + \mathbb{E}[P]\right]}{(1-p_{tr})\sigma + p_{tr}(1-p_{suc})T_{col} + p_{tr}\cdot p_{suc}\cdot T_{ed}}. \end{aligned} \tag{57}$$

4) ENERGY EFFICIENCY

The energy efficiency is defined as the energy utilized in successfully transmitting bits with the total energy consumption. Let E_e be the energy efficiency and

$$E_e = \frac{p_{suc}\cdot E_P}{E_{col}(1-p_{suc}) + E_{succ}\cdot p_{suc}}. \tag{58}$$

where $E_P = P_n \cdot T_P$ is the energy consumed in a packet payload transmission.

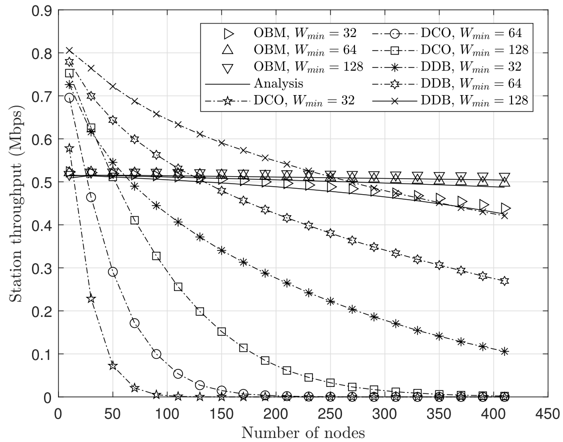

FIGURE 6. Throughput of wireless devices for varying number of nodes and W_{min}, (marker: simulation, line: analysis).

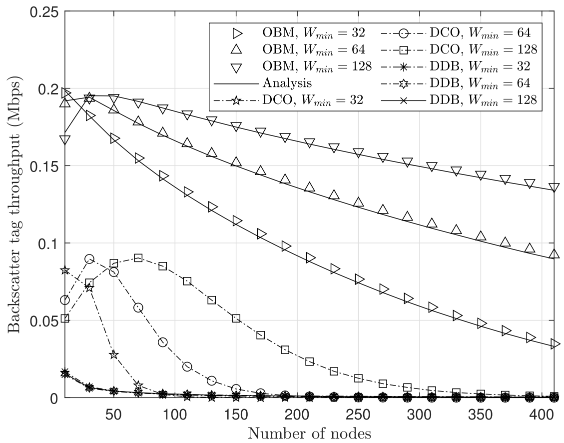

FIGURE 7. Throughput of the backscatter tags for varying number of nodes and W_{min}, (marker: simulation, line: analysis).

V. PERFORMANCE EVALUATION

We evaluate the performance of the proposed scheme by a detailed analysis and verified it through extensive simulations. The proposed scheme gives an opportunity to coexist wireless data transmission, wireless energy harvesting and backscatter communications in a network. An example of network model is given in Fig. 1 where backscatter tags communicate with the reader underlying a wireless energy harvesting network in a free space environment [42]. The system parameters given in Table. 1. Wireless devices are distributed on a disc D with a radius r of a device. The performance of the proposed OBM protocol is compared with DCO and DDB channel access mechanisms [31], [32]. The DCO protocol gives backscatter tag an opportunity to contend with wireless devices in a heterogeneous communication network. The DDB protocol is an on-demand protocol which lets the AP contends with wireless devices. The AP triggers the backscatter tags by sending the preamble to stimulate them for contention and communication when it succeeds.

Fig. 6 illustrates the performance of the proposed scheme in terms of throughput, along with a comparison to other schemes, for varying numbers of nodes in a heterogeneous network. The focus of the analysis is on the throughput

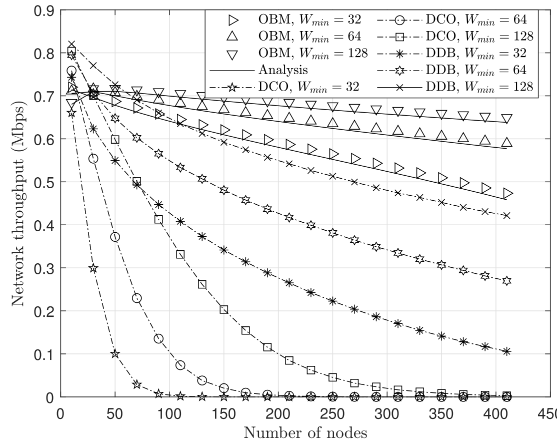

FIGURE 8. Network throughput for varying number of nodes and different minimum backoff window W_{min}, (marker: simulation, line: analysis).

of wireless devices in the presence of both backscatter tags and wireless devices contending for channel access. The proposed scheme explores the influence of the binary exponential backoff mechanism on the network by varying the minimum backoff window, denoted as W_{min}. In the proposed scheme, the utilization of the energy harvesting duration for backscatter communication effectively mitigates inter-collision between wireless devices and backscatter tags. This leads to improved throughput for wireless devices. As the number of nodes increases, the throughput of all nodes decreases due to the impact of collisions on network performance. This impact is more evident in the comparative schemes. However, the proposed scheme maintains a consistent throughput compared to the comparative schemes. For instance, when the minimum backoff window $W_{min} = 128$, it results in better throughput compared to a $W_{min} = 32$, especially for a higher number of nodes. This is because a larger backoff contention window increases the number of idle slots, thus reducing the probability of collision. The collision mitigation achieved through the larger contention window significantly benefits the performance of the proposed scheme compared to the conventional scheme.

Fig. 7 illustrates the throughput of backscatter tags in the network as a function of the number of nodes and the backoff contention window. The backscatter tags contend for channel access during the wireless energy transmission duration provided by the HAP. The plot demonstrates that the backscatter tags consistently achieve a stable network throughput, due to the collision-resilient access control method employed. In contrast, the conventional schemes exhibit a decreasing trend in throughput as the number of nodes increases. This decline in throughput is attributed to the increased probability of collisions with a larger number of nodes contending for access. As collisions occur, it negatively impacts the throughput of the backscatter tags. The impact of the backoff window is notable as it helps reduce collisions by providing a larger window size for contention. This increase in window size leads to improved throughput for the backscatter tags. However, it is important to note that increasing the size of the backoff window also increases the number of idle slots, which may result in decreased throughput. Therefore, there is a trade-off between achieving successful transmissions, reducing collisions, and managing idle events. This trade-off can be effectively managed based on the congestion status of the backscatter tags within the network.

Fig.8 depicts the throughput of the network as the number of contending nodes varies. The network's throughput is influenced by the successful transmission of bits by both wireless energy harvesting devices and backscatter tags. When a larger number of nodes contend for channel access, the transmissions become more susceptible to interference and collisions, resulting in reduced network throughput. The proposed scheme demonstrates consistent network performance compared to the conventional schemes. This is achieved through the implementation of a handshaking mechanism among the contending nodes, including wireless energy harvesting devices and backscatter tags, which effectively mitigates collisions. Additionally, the opportunistic backscatter communication further enhances the network throughput by utilizing the energy harvesting duration for transmitting information through backscatter tags. In contrast, the conventional schemes are more affected by transmission collisions, leading to a decrease in network throughput. However, the network throughput improves as the backoff window in the Distributed Coordination Function (DCF) is increased. This increase in the backoff window allows for more successful transmissions by the Access Point (AP), thereby providing more opportunities for the backscatter tags to communicate. For the DCO protocol, its performance is improved when the backoff contention window is increased. This adjustment helps reduce collisions, resulting in enhanced network throughput. It is worth noting that the backscatter tags contend in parallel with wireless devices, which may contribute to an increase in transmission collisions. Overall, the proposed scheme's consistent network performance, facilitated by the handshaking mechanism and opportunistic backscatter communication, contributes to improved network throughput. On the other hand, the conventional schemes are more affected by transmission collisions, resulting in reduced network throughput.

Fig. 9 presents the energy efficiency of nodes in relation to increasing network density and the minimum backoff contention window, denoted as W_{min}. The proposed scheme is designed to leverage available energy resources for successful data transmission, thereby reducing energy waste caused by transmission collisions through the implementation of a handshaking mechanism. As a result, the proposed scheme achieves improved and consistent energy efficiency across different network densities. In contrast, the conventional schemes exhibit a decrease in energy efficiency as the network density increases. This decline in energy efficiency is attributed to the increased occurrence of transmission collisions in denser networks. However, when the backoff contention window is increased (i.e., a larger W_{min} value), the conventional schemes are able to achieve higher energy

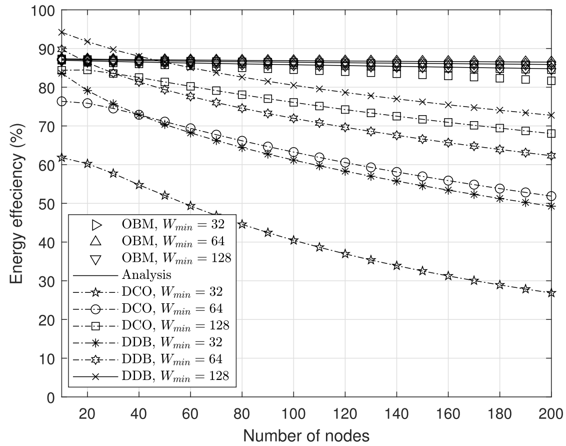

FIGURE 9. Energy efficiency for varying number of nodes and W_{min}, $b = 20$, $P_B = 10W$ and $r = 5$, (marker: simulation, line: analysis).

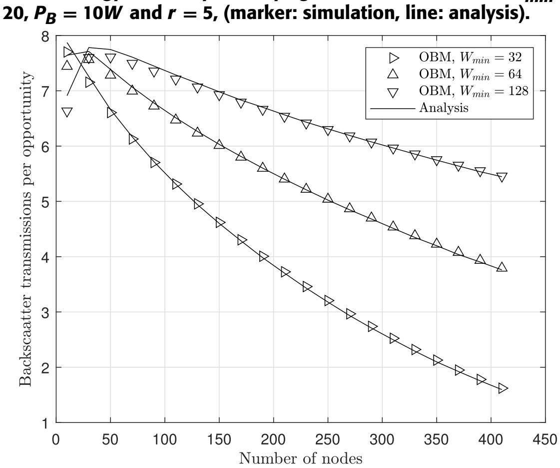

FIGURE 10. Average number of opportunistic backscatter transmissions for varying number of nodes and W_{min}, (marker: simulation, line: analysis).

efficiency. This is because the larger window size reduces the probability of collision, thereby improving energy efficiency. On the other hand, the proposed scheme outperforms the conventional schemes in terms of energy efficiency. This is primarily due to its collision-resilient contention mechanism, which allows for more efficient utilization of energy resources. By effectively mitigating collisions, the proposed scheme achieves better energy efficiency compared to the conventional schemes.

Fig. 10 displays the average number of opportunistic backscatter transmissions that occur during the assigned time period. By utilizing the energy harvesting duration, the proposed scheme enhances network throughput. As the number of nodes increases, the average number of successful backscatter transmissions decreases. This reduction is primarily caused by the higher probability of collisions due to the increased contention among the nodes. A higher average number of opportunistic backscatter transmissions during the assigned time period contributes to improved network throughput. This is because these transmissions effectively utilize the available resources and increase the overall data exchange within the network. The increase of the backoff window size helps minimize collisions, thereby increasing the average number of opportunistic backscatter transmissions. However, it is important to note that for a low density of contending nodes, a larger backoff window may result in more frequent idle slots. Consequently, this can have an adverse effect on network throughput. Therefore, it is essential to carefully control the occurrence of collisions, successful transmissions, and idle slots based on the congestion level within the network. This ensures an optimal balance that maximizes network throughput in the proposed scheme.

The proposed opportunistic backscatter communication scheme provides a medium access control protocol for the coexisting wireless powered communication and backscatter communication network. It has solved the research problem in terms of energy efficiency and network throughput. First, it enhances the network efficiency by utilizing the wireless powered transmission for backscatter communication in the heterogeneous wireless communication network. Second, the energy efficiency is also enhanced by reducing the collision of transmission by distributed contention mechanism. Third, it provides a mechanism to coexist the wireless data communication and wireless energy harvesting in a distributed mechanism. Fourth, the proposed OBM scheme uses collision mitigation mechanism using distributed contention mechanism enhances the throughput of the wireless devices and backscatter tags leading to enhancement of overall network throughput. Fifth, the collision mitigation mechanism increases the network density. The proposed scheme use a binary exponential backoff mechanism which significantly reduces the transmissions as compared to the existing schemed leading to enhanced network performance in terms of energy efficiency and network throughput.

The outcome's substantial impact on the research field are; (i) A backscatter communication tags network can be established underlying wireless powered IoT network. (ii) The underlying network can coexist with the existing wireless communication network using a distribution mechanism. (iii) The energy in the air can be usefully utilized for the backscatter communication. Thus. it enhances the energy efficiency. (iv) The backscatter communication enables the overall network for communicating more data in less time which enhances the network throughput. (v) We can estimate the number of contending nodes, wireless devices and backscatter tags giving the insights of network density.

VI. CONCLUSION

The proposed scheme addresses the challenges of integrating backscatter tags and wireless energy harvesting devices in a heterogeneous IoT network. The goal is to enable efficient coexistence between backscatter communications and wireless powered communication networks. To achieve this, an opportunistic backscatter communication MAC scheme has been developed. In this scheme, wireless devices within the network contend for channel access in order to perform two main functions: energy harvesting and communication with the HAP. The HAP serves as a source of wireless power signals, which are utilized by the backscatter tags to establish a connection with the reader's wireless powered communication network. By leveraging the available energy harvesting time and RF signals, the backscatter tags are able to backscatter data to the reader, leading to an increase in network throughput. The scheme investigates important parameters such as the transmission probability, collision probability, and success probability of both wireless devices and backscatter tags. Furthermore, the average number of opportunistic broadcasts during the available period is also determined. Compared to traditional systems, the suggested opportunistic backscatter MAC scheme demonstrates significant improvements in network performance. These improvements are evident in terms of enhanced throughput and increased energy efficiency. The scheme provides a comprehensive solution for efficient and effective utilization of resources in the heterogeneous IoT network, thereby enabling seamless coexistence between backscatter communications and wireless powered communication networks.

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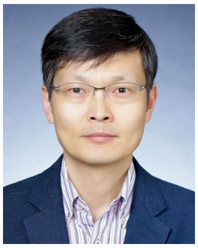

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