Backscatter MAC Protocol for Future Internet of Things Networks

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***Abstract*—Backscatter wireless communication (BWC) is a promising research area for the low power Internet of Things (IoT) devices. A substantial number of research works have been conducted in this area to increase the range of BWC. Along with physical layer achievements in BWC, an efficient medium access control (MAC) protocol is mandatory to attain the optimal benefit. In this paper, a novel MAC protocol is proposed to support BWC in a Wi-Fi network, where the AP and the Wi-Fi clients are capable of in-band full-duplex (IBFD) transmission, but the wireless tags (WTags) are half-duplex capable. In this MAC protocol, the AP suppresses the uplink transmission of the corresponding Wi-Fi client while transmitting the downlink data to support the BWC. Some new control frames have been introduced to facilitate this task. A mathematical analysis of this proposed MAC is presented here together with an evaluation of its performance. The mean overhead time is observed as 121 μs with the downlink utilization factor of 80%. The average throughput of the network decreases as the number of WTag increases. This average throughput is observed as 63.5 Mbps and 59 Mbps (with 30 WTags and 30 Wi-Fi clients) for the data delivery frequency of two times/WTag and eight times/WTag respectively.**

***Keywords*-Backscatter communication; MAC protocol; wireless tag; Internet of Things (IoT).**

I. Introduction

Nowadays, the world of communication is dominated by Internet. Based on this technology, Internet of Things (IoT) is becoming a important paradigm, by which everything can be accessed and/or controlled remotely [1]. To facilitate this system, IoT depends on machine-to-machine communications, where different kinds of smart electronic devices are used such as sensors, actuators, wearable devices and metering devices. The future IoT network can be defined as the network that consists of smart IoT devices and in-band full-duplex (IBFD) capable network devices such as the access point (AP) and/or the Wi-Fi clients. A typical structure of the future IoT network is depicted in Fig. 1, where the AP and the clients are IBFD capable and the wireless tags (WTags) are HD capable. The WTags are the low power radio-frequency identification (RFID) tags that can backscatter the received signal. IBFD capable devices can transmit and receive data simultaneously by using the same frequency channel, which is performed by utilizing self-interference cancellation technique [2]. Therefore, the IBFD transmission in wireless communications can potentially double the spectral efficiency relative to the conventional half-duplex (HD) operation [2].

The IoT devices are designed as low power devices and researchers in this area are trying to find out the way for lower consumption of power for these devices. For example, Bluetooth Low Energy (BLE) for low-power communication consumes tens of milliwatts in active mode i.e. in the data transmission mode; however, a backscatter tag consumes a few micro-watts in the transmitting mode [3]. Therefore, the backscatter wireless communication (BWC) is one of the best candidates to minimize the power consumption. Moreover, the existing bandwidth can be utilized by using BWC. Therefore, additional frequency spectrum is not required for these kinds of IoT devices that can perform BWC.

The functional diagram of the WTag is shown in Fig. 2. As shown in the figure, the receiver of the WTag can receive the continuous pulses of ‘1’ and ‘0’ with a fixed duration of the pulse. However, the transmitter sends data to the AP by modulating the Wi-Fi channel as seen by the client. It conveys ‘1’ by reflecting the signal and conveys ‘0’ by absorbing the signal [4]–[6]. A typical BWC is depicted in Fig. 3. Here, a

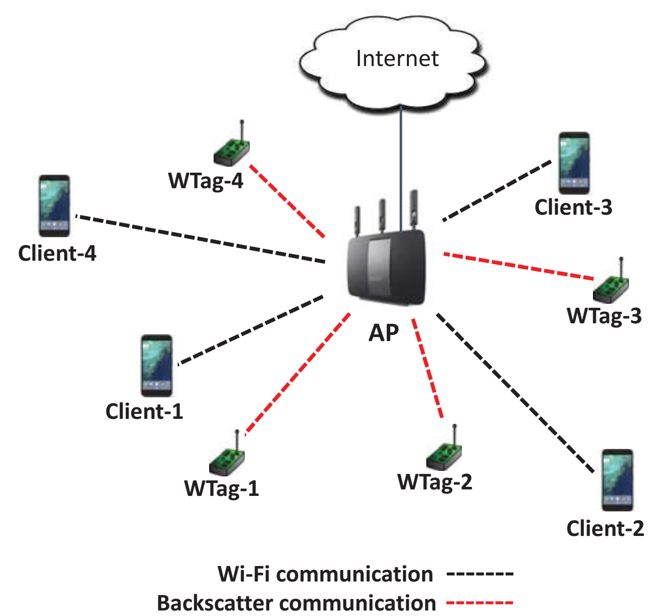


Fig. 1. Structure of a future IoT network that supports BWC. The AP and all clients are IBFD capable. All WTags are HD capable.

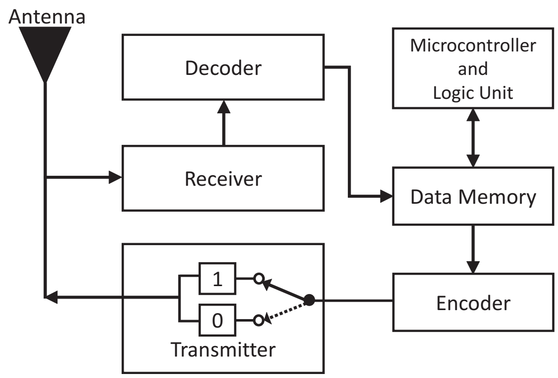


Fig. 2. The functional diagram of the WTag.

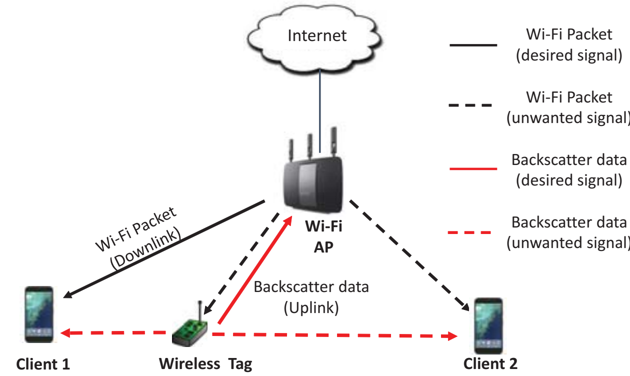


Fig. 3. A typical backscatter wireless communication for a WLAN.

Wi-Fi AP sends packets to the client-1. The WTag sends data to the AP by modulating the Wi-Fi channel as seen by the client-1. It transmits '1' by reflecting the signal and transmits '0' by absorbing the signal (Fig. 3).

In this paper, a medium access control (MAC) protocol is proposed for the BWC, which can be utilized in the future IoT network that has an IBFD capable AP, IBFD capable clients and HD capable WTags as shown in Fig. 1. This MAC protocol can be incorporated with another IBFD MAC design. This MAC protocol is suitable for those WTags, whose frequency of sending data is low. In this MAC protocol, the AP selects individual WTag to send their data. The main contributions of this paper are listed below:

- This is a novel MAC protocol that supports BWC in Wi-Fi networks.
- This MAC protocol is suitable for those IoT devices that have lower frequency of data delivery to the AP.
- In this MAC, the AP transmits dummy packets, if it has no downlink data during the offering of BWC.
- During the BWC, the AP suppresses all the uplink transmissions from the clients to the AP, even if the corresponding client has data to send; i.e. along with other uplink transmissions, the bi-directional communication is also suppressed due to support the BWC.

The rest of this paper is arranged as follows: Section-II describes the related researches in this area, Section-III provides a brief description of the problem statement regarding the BWC, Section-IV describes the proposed MAC design, Section-V presents the mathematical analysis, and Section-VI contains the results and performance analysis.

II. Related Works

A number of experimental evaluations have been performed in recent years for the BWC. An experimental evaluation is performed for the BWC in [4]. In that paper, the radio frequency (RF) powered devices performed BWC to access the Internet by using the existing Wi-Fi infrastructure. Here the BWC is performed at a maximum distance of 2.1 m with the rates of upto 1 kbps. Here, the RF devices establish the connection to the Internet via the existing Wi-Fi infrastructure. BackFi utilizes IoT sensors in the Wi-Fi network by using BWC [5]. In BackFi, the IBFD capable AP was used as the Wi-Fi reader and the self-interference cancellation technique was modified to support BWC. The backscatter communication range is extended in that evaluation upto 5 meter. The passive Wi-Fi enables to generate IEEE 802.11b transmission by using BWC [6]. The operational range of the BWC is further extended upto 100 feet in passive Wi-Fi. However, the passive Wi-Fi transmitters need additional association procedure for the plugged-in device and Wi-Fi router. Therefore, it requires higher overhead in passive Wi-Fi.

In addition, a substantial number of physical layer experiments for BWC have been performed by using ambient radio frequency (RF). The ambient BWC experiment was performed by using existing TV and cellular RF signal [7]. That physical layer experiment achieved the backscatter data rate of 1 kbps over distances of 2.5 feet and 1.5 feet in case of outdoors and indoors respectively. However, another research has extended the range of BWC by introducing a new coding system and multi-antenna cancellation receiver [8]. That experiment extended the communication range upto 80 feet with the data rate of 1 Mbps. Some other physical layer analyses on BWC have been also done in recent years [9], [10].

The frequency of data transmission by the IoT devices to the AP varies depending on applications. In some cases it is once/twice a day, or even lower in some other cases. For example, the data delivery frequency of the sensors that is used for gas and water monitoring, can vary from once/twice in a month. The frequency of data delivery depends on applications, as there are different kinds of applications in these areas, such as gas and water meter monitoring, pipe line monitoring, detection of gas monitoring, etc. [11]. For example, a remote indoor environment monitoring is performed in a building and the real time sensor data is displayed on a web browser-enabled device [12]. The sensors in that experiment read and transmit data every 15 minutes. Another real-time energy monitoring is performed by using smart meter (SM) in Italy [13]. The metering data from SMs are collected by data concentrators on a monthly basis and the data is sent by using the telecommunications network.

III. Problem Statement

- The research works on BWC mentioned in Section-II are performed on physical layer, where the MAC protocol is not considered. As long as the range of of the BWC is short (within 1 or 2 meter), the MAC protocol is not so vital. However, the researchers are giving their effort to extend the range of the BWC. The communication range of BWC is achieved upto 5 meter in Wi-Fi networks [5] and 30 meter in passive Wi-Fi [6]. This range of BWC is about 25 meter by using TV signal [8]. Therefore, we do believe that the communication range of BWC in Wi-Fi networks will be further extended in near future. Therefore, to attain the full leverage of BWC in future Wi-Fi networks, an efficient MAC protocol is crucial.
- In most of the experimental evaluations, the AP transmits a continuous long packet, so that the WTag can backscatter its data to the AP. For example, the AP transmits 1 to 4 ms (3000 bytes to 12000 bytes) long byte at 24 Mbps [5]. However, this is not practical, as the usual packet or frame length in existing Wi-Fi network is about 1500 bytes. Moreover, if the AP stops its transmission, the backscatter communication is interrupted. Therefore, there is a high probability of missing backscatter data. There is no exact guideline in the recent experimental evaluations of BWC that how this problem can be solved.
- Some researches have been conducted for BWC by using existing TV signal. As TV signals are broadcasted continuously, the problem mentioned earlier does not occur here. However, this kind of BWC cannot be utilized in traditional WLANs, as the frequency ranges are different.
- Moreover, the frequency of data delivery to the AP is different based on the application of the WTag, which is discussed in Section-II. For example, the WTag needs to transmit its collected data once a day or even once a month for some cases [13]; such as electric, water, gas meter reading, etc. However, in some other cases, the WTag needs to transmit the data at very short intervals. For example, real time road traffic monitoring requires data very frequently. As the different WTags are used for different applications, different scheduling or different MAC protocols are also required based on the applications of the WTag.

IV. Proposed MAC Protocol

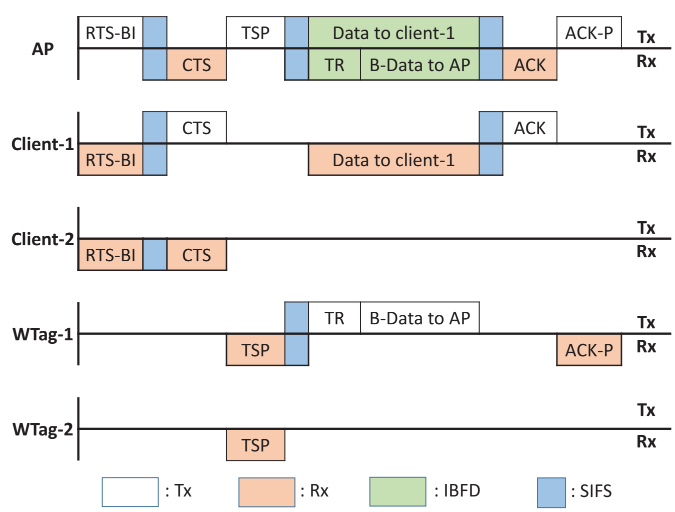
This backscatter wireless MAC protocol is designed for the WTag, whose data transmission frequency is lower. This MAC design can be utilized with other IBFD MAC protocols for the Wi-Fi infrastructure. This is a query based MAC protocol, where the AP selects the WTag to send its collected data. Therefore, the normal data communication is performed by using any existing IBFD MAC protocol. However, this proposed MAC protocol will take place, when the AP offer the BWC. The network structure, for which this MAC can be utilized is shown in Fig. 1. Here, the AP as well as all clients are IBFD capable and the WTags are HD capable. Here, the WTags perform the backscatter communication for sending data to the AP. Therefore, the AP requires to have a modified self-interference cancellation technique that is described in [5]. Every WTag has a unique ID. The AP knows the data transmission time of the WTags, which is configured during the installation procedure, or it can be performed in the association procedure. The BWC is offered by the AP as the following two ways:

A. The AP has downlink data

The AP offers the BWC to every WTags according to a predefined time. During this offering of BWC, the AP may have downlink data or not. If the AP has downlink data, it broadcasts request to send (RTS) with backscatter indicator (RTS-BI) to a client, whom the AP wants to send its downlink data. The data transmission sequence is shown in Fig. 4. The backscatter indicator (BI) is a one bit value, which is appended to the normal RTS to obtain RTS-BI.

The formats of all control frames used in this MAC protocol are shown in Fig. 5. Some new control frames are introduced in this MAC protocol to facilitate the BWC, such as tag selection pulses (TSP), tag's reply (TR), acknowledgement pulses (ACK-P) and dummy RTS with BI (DR-BI). The control frames for Wi-Fi clients are transmitted according to IEEE 802.11 standard and these are RTS-BI, clear to send (CTS), ACK and DR-BI as shown in the Fig. 5. However, the controls frames for the WTags are transmitted as the continuous pulses of '1' and '0' with a fixed duration of the pulse and these control frames are TSP, TR and ACK-P.

If the AP has downlink data during the offering of BWC, it sends RTS-BI. By sending RTS-BI, the AP informs all clients that the BWC is going to take place in this current data



RTS-BI: RTS with backscatter indicator, **CTS**: Clear to send, **TSP**: Tag Selection Pulses, **TR**: Tag's Reply, **B-Data**: Backscatter data, **ACK**: Acknowledgement, **ACK-P**: ACK pulses for the WTag.

Fig. 4. Time sequence of the proposed MAC (the AP has downlink data).

transmission phase and it wants to send the downlink data to client-1 as shown in Fig. 4. In this case, the BI value is “1”. All other clients refrain to transmit any data within the time that is declared in RTS-BI. In addition, if the corresponding client (client-1 in this case) is IBFD capable and it has also data to send the AP, the client also refrain to transmit uplink data in this transmission cycle. After receiving RTS-BI, client-1 sends CTS. Other clients (such as client-2 in the figure) overhear the control frames or other transmitted data in the network.

The AP sends the tag selection pulses (TSP), after receiving CTS. The TSP is a series of short pulses, which contains the ID of the WTag and the duration of downlink data transmission time. Therefore, the corresponding WTag (WTag-1 in Fig. 4) will be informed about the BWC. After that, the AP starts to send the downlink data to the client-1 as shown in the figure. WTag-1 sends tag’s reply (TR) by backscattering to the AP. It confirms its identification and informs the duration of its data transmission time by sending the TR. As the WTag’s ID is known to the AP, the AP can estimate the backscatter wireless channel during the backscattering of TR. After sending TR, the WTag sends the backscatter data (B-Data) to the AP. The acknowledgement (ACK) is sent by client-1 to the AP at the end of the data transmission. The AP sends ACK-P to WTag-1. ACK-P is a sequence of pulses that contain address of WTag-1, which is unique for each individual WTag. Other tags such as WTag-2 overhear the control frames as well as other data.

The duration in TSP (D-duration) and the duration in TR (B-duration) are used for a reason. The interpretation can be written as the following two cases:

a) if B-duration $>$ D-duration, WTag has more data to send;

b) if B-duration $<$ D-duration, WTag has finished its transmission.

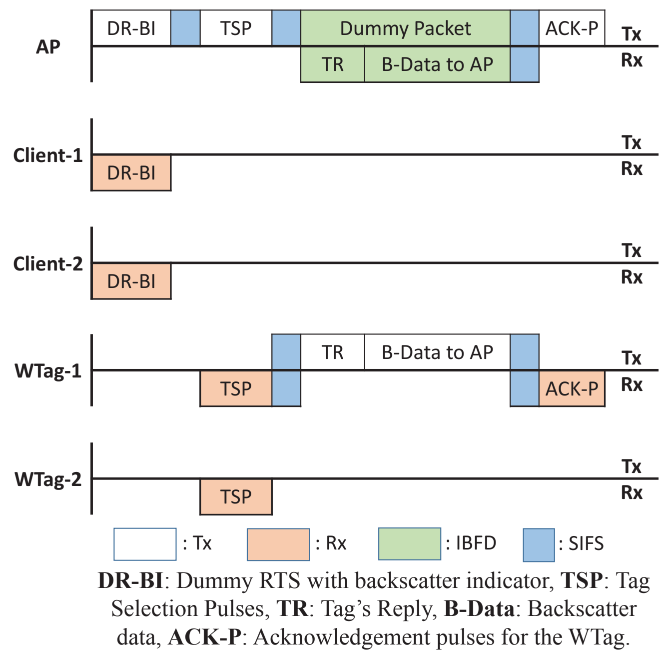


Fig. 6. Time sequence of the proposed MAC (the AP has no downlink data).

Therefore, after receiving the TR from the WTag, the AP can decide about the remaining data of the corresponding WTag. The AP selects the same WTag in the next data transmission cycle, if B-duration $>$ D-duration. Otherwise, it selects another WTag, based on the availability as well as on the schedule.

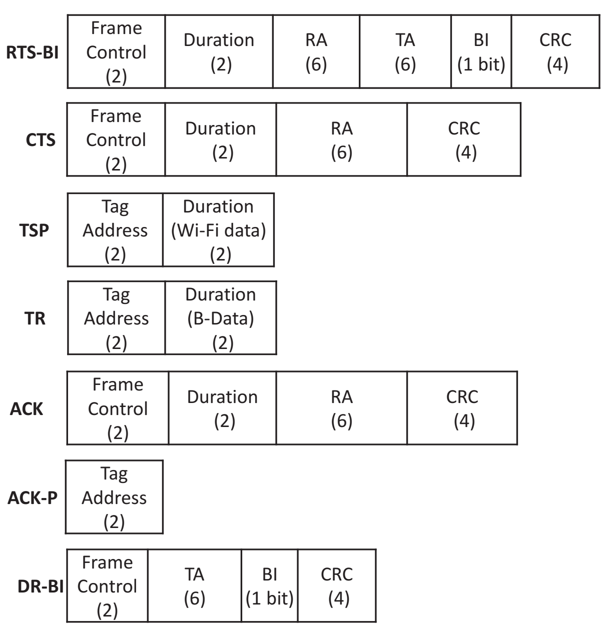


Fig. 5. Format of control frames (in octet).

B. The AP has no downlink data

It may happen that the AP needs to offer BWC for a WTag, but it does not have any downlink data. In that case, the AP broadcasts dummy RTS with BI (DR-BI) as shown in Fig. 6. The DR-BI informs all the clients that the BWC is going to take place now and therefore, the clients are not allowed to initiate any data transmission for the defined duration that is mentioned in the DR-BI. After transmitting DR-BI, the TSP is transmitted by the AP for selecting the WTag, which is followed by dummy packet transmission as shown in Fig. 6. After receiving the dummy packet, the corresponding WTag (WTag-1 in the figure) sends TR by using BWC. By sending TR, the WTag sends its ID as well as the duration of B-Data. After that, WTag-1 sends its B-Data to the AP. At the end of the transmission, the AP transmits ACK-P to WTag-1.

V. Mathematical Analysis

A. Probability Calculation

It is assumed that the packet arrival rate (PAR) follows the Poisson arrival process and the service time is deterministic. Therefore, the system follows the characteristics of M/D/1 queueing system. Total PAR at the AP from the Internet as downlink packets is defined as:

$$\lambda_{\mathrm{D}} = (\lambda_{\mathrm{d1}} + \lambda_{\mathrm{d2}} + \cdots\cdots \lambda_{\mathrm{dn}})$$
$$\Rightarrow \lambda_{\mathrm{D}} = \sum_{i=1}^{n} \lambda_{\mathrm{d}i} \quad (1)$$

where, n is the total number of Wi-Fi clients, λ_{d1} is the downlink PAR at the AP for client-1, λ_{d2} is the downlink PAR at the AP for client-2 and so on. If the PAR at the AP for each client is the same, (1) can be written as

$$\lambda_{\mathrm{D}} = n\lambda_{\mathrm{d}} \quad (2)$$

where, λ_d is the downlink PAR at the AP for each client.

Similarly, total packet generating rate (PGR) by the Wi-Fi clients as uplink packets to the AP is:

$$\lambda_{\mathrm{U}} = (\lambda_{\mathrm{u1}} + \lambda_{\mathrm{u2}} + \cdots\cdots \lambda_{\mathrm{un}})$$
$$\Rightarrow \lambda_{\mathrm{U}} = \sum_{i=1}^{n} \lambda_{\mathrm{u}i} \quad (3)$$

where, λ_{u1} is the uplink packet that is generated by client-1 to the AP, λ_{u2} is the uplink packet that is generated by client-2 and so on. If the PGR by each client is the same, (3) can be written as,

$$\lambda_{\mathrm{U}} = n\lambda_{\mathrm{u}} \quad (4)$$

where, λ_{u} is the PGR by each client.

The BWC is performed by using either downlink packet or dummy packet. Therefore, we need to find out the probability of downlink packet from the AP to the clients. If the AP has no downlink packet during the offering of the BWC, it transmits dummy packet. Therefore, the probability of transmitting dummy packet (P_{D1}) is the same as the probability that AP has no downlink data (P_0) during the offering of BWC, which can be written as:

$$P_{\mathrm{D1}} = P_0 = e^{-\lambda_D T_{\mathrm{w}}} \quad (5)$$

where, T_{w} is the average waiting time for a downlink packet according to the M/D/1 system.

The probability that the AP has at least one downlink packet (P_{D2}) during the offering of BWC is given by the following equation:

$$P_{\mathrm{D2}} = 1 - P_0 = 1 - e^{-\lambda_D T_{\mathrm{w}}} \quad (6)$$

B. Overhead Calculation

The overhead of this proposed MAC can be calculated from the time sequences as shown in Fig. 4 and Fig. 6. If the AP offers the BWC with the downlink data to a Wi-Fi client, the total overhead time of the transmission cycle can be written as:

$$T_1 = T_{\mathrm{RTS-BI}} + 3T_{\mathrm{SIFS}} + T_{\mathrm{CTS}} + T_{\mathrm{TSP}} + T_{\mathrm{ACK}} + T_{\mathrm{ACK-P}} \quad (7)$$

The meaning of the symbols are given in Table. I. However, the AP sends dummy packet, if it has no downlink data during the offering of the BWC. Therefore, the total overhead time is obtained from Fig. 6 is given as:

TABLE I
DECLARATION OF VARIABLES

Variables	Explanation
T_1	Total overhead time of the transmission, when the AP has downlink data
T_2	Total overhead time of the transmission, when the AP has no downlink data
T_{ACK}	Transmission time of ACK
$T_{\mathrm{ACK-P}}$	Transmission time of ACK-P
T_{CTS}	Transmission time of CTS
$T_{\mathrm{DR-BI}}$	Transmission time of DR-BI
$T_{\mathrm{RTS-BI}}$	Transmission time of RTS-BI
T_{SIFS}	SIFS time
T_{TSP}	Transmission time of TSP
P_{D1}	The probability that the AP transmits dummy packet
P_{D2}	The probability that the AP transmits downlink data

$$T_2 = T_{\mathrm{DR-BI}} + 3T_{\mathrm{SIFS}} + T_{\mathrm{TSP}} + T_{\mathrm{ACK-P}} \quad (8)$$

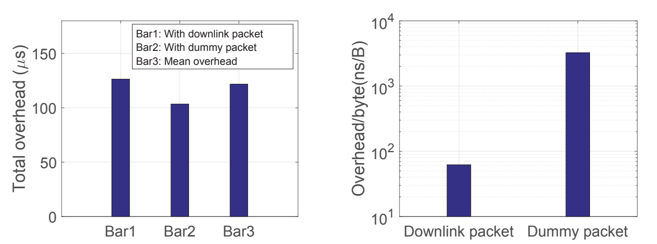
The expected value of the total overhead time, after offering BWC can be calculated as:

$$T_{mean} = T_1 \times P_{\mathrm{D2}} + T_2 \times P_{\mathrm{D1}} \quad (9)$$

VI. RESULT AND PERFORMANCE ANALYSIS

The performance of this MAC protocol is performed by using MATLAB simulation. The overhead of this proposed MAC is shown in Fig. 7. The simulation parameters are shown in Table II. It is observed that total overhead time is 126 μs, if the AP has downlink data during the offering of BWC. However, this overhead time is 103 μs, if the AP has no downlink data during the offering of BWC as shown in Fig 7(a). The mean overhead time is obtained as 121 μs. The downlink utilization factor is assumed to be 80% for the calculation of mean overhead time.

Another overhead comparison is depicted in Fig. 7(b) in terms of overhead/byte (ns/B). The performance of a MAC protocol cannot be compared only by total overhead. It is



(a) Total overhead time(μs) (b) Overhead/byte (nanosecond/B)

Fig. 7. Overhead comparison

TABLE II
SIMULATION PARAMETER

Parameter	Value
Downlink packet length	2000 bytes
Dummy packet length	2000 bytes
Data rate	54 Mbps
Control frame (RTS-BI, CTS, etc.) rate for Wi-Fi clients	12 Mbps
Control frame (TSP, TR, etc.) rate for WTags	1 Mbps
Backscatter data rate	1 Mbps
SIFS time	10 μs
PLCP preamble duration	16 μs
PLCP header duration	4 μs
Number of Wi-Fi clients	30
Number of WTags	30
Downlink utilization factor	80%

required to compare in terms of overhead/byte (ns/B), by which it can be realized about the amount of transmitted data. If the BWC is performed by using the downlink data from the AP to a Wi-Fi client, about 62 ns/byte overhead is observed. However, this overhead becomes 3000 ns/byte, if the BWC is performed by using the dummy packet. This performance analysis suggests that the BWC should be utilized by using the downlink data for the AP to a client, as it has lower overhead per byte. However, if the AP has no downlink data, it can accept this higher overhead for facilitating the BWC.

The performance in terms of throughput is shown in Fig. 8. This simulation is performed under saturation condition. The saturation condition is defined as the situation in which all the active devices in the network has data to send, i.e. the transmission queues of all clients and the AP are nonempty in saturation condition [14], [15]. As this MAC protocol is designed for the WTags that transmit data in lower frequency of data delivery such as once or twice a day. Therefore, this proposed MAC can be incorporated with other existing MAC protocol, where the AP is IBFD capable as well it can support BWC. In this simulation, this MAC is incorporated with a existing MAC that is proposed to support the asymmetric traffic length for uplink and downlink [16]. Therefore, normal Wi-Fi traffic is transmitted according to the existing MAC protocol [16]. On the other hand, the proposed backscatter MAC protocol is performed, when the AP offer the BWC.

According to the proposed MAC protocol, the AP selects the WTag during the offering of the BWC. In saturation condition, the number of total transmission is almost same for a specific observation time. In this simulation, the total number of transmission is considered as 1000 including all BWC from all WTags. Therefore, the average throughput is decreasing for two reasons as shown in Fig. 8. Firstly, the AP suppresses the Wi-Fi client to transmit uplink data to the AP during the offering of BWC. As the transmission data rate of BWC is much lower than that of the Wi-Fi transmission, the average throughput decreases. Secondly, if the number of WTags as well as the data transmission frequency of WTags increases, the number of offering BWC by the AP also increases and thus the average throughput decreases. It is observed that the average throughput of the network is almost same for the lower number of WTags (upto 8 WTags), even if the frequency of data delivery increases from 2 to 8. However, the difference of average throughput is significant for those cases, if the number of WTags increases to 30. For example, the average throughput is observed as 63.5 Mbps and 59 Mbps for 30 WTags, if the transmission frequencies are two times/WTag and eight times/WTag respectively (Fig. 8).

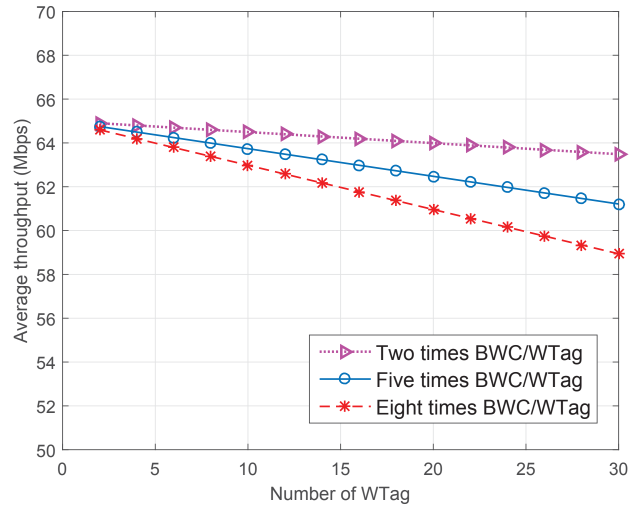


Fig. 8. Average Throughput under saturation condition.

The result from Fig. 8 suggests that the offering time of the BWC in a Wi-Fi network should be scheduled during the time when the network is in unsaturation condition; for example the traffic load is much lower at night. Moreover, this result suggests that too many WTags in the Wi-Fi network will reduce the overall throughput of the network, as the data transmission rate of the BWC is much lower than that of the Wi-Fi.

VII. CONCLUSION

A MAC protocol is proposed in this paper for backscatter wireless communication for Wi-Fi networks. Here, the AP offers backscatter wireless communications for the wireless tag by suppressing the uplink data transmission opportunity of the Wi-Fi client. The proposed backscatter MAC is suitable for the tags that has lower frequency of data delivery to the AP. This research work suggests that the average network throughput decreases as the number of tags increases. Therefore, the incorporation of huge number of tags in a Wi-Fi network will degrade the overall network performance. Further research will be conducted to extend this MAC to access the channel randomly by the tags.

Acknowledgment

This research and development work is supported by the MIC/SCOPE # 155007006. This work is also supported by JSPS KAKENHI Grant Number JP16H01718.

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