N-Element Beam Antennas System Design for Wireless Sensor Node Using Semi-Markov Decision Process with Variable Sojourn Time

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***Abstract*—The paper presents *N*-element switchable beam antennas (BAs) system design for Wireless Sensor Node (WSN), in which the operation of the BAs was characterized by semi-Markov Decision Process (SMDP) with variable sojourn time. A matrix-based switching methodology was introduced for selecting an operational BA, based on the received signal power by each BA. Optimal analysis was carried-out to obtain optimal results in terms of the maximum total of sum of discounted reward in current states. Also developed in the study is the methodology for switching a BA from non-operational to operational state and vice-versa. The effectiveness of this switchable BAs system design was tested via numerical analysis implemented in MATLAB software. Numerical results show that this novel approach enables the WSN equipped with BAs to select and maintain an operational BA in receive (or transmit) mode for the entire duration of packets reception (or transmission). The authors found no paper in the existing literature that provides this capability.**

***Index Terms*—Beam antennas, wireless sensor node, semi-Markov decision process, sojourn time**

I. Introduction

Beam (or directional) antennas system radiates (or receives) greater signal power in one direction than the other during a given antenna system scanning period. By using BAs, a WSN is able to selectively receive signals only from a desired direction. An important advantage of this directional selectivity is that the receiver sensor node can avoid interference that comes from undesirable direction(s). In the IEEE 802.11 Distributed Coordinated Function (DCF) protocol, exchange of the request-to-send (RTS) and clear-to-send (CTS) packets takes place before the data communication [1]. The RTS and CTS packets include the duration field that contains the intended duration for data transmission. All packets have Duration Value (DV). The DV indicates the time needed to transmit all the remaining data fragments and acknowledgment (ACK) packets. Moreover, the DV is stored by every IEEE 802.11-based system in the Network Allocation Variable (NAV). In the existing literature, researchers have used different approaches and segment arrays for BAs systems design. A planar directional beam-switchable antenna with four orthogonal beam directions was designed in [2]. This antenna is equipped with two crossed active elements and two parasitic elements for each direction. The planar architecture design approach is described based on the Yagi-Uda method ([3]-[5]) for the active and parasitic elements, respectively. In addition, the authors used various parasitic structures in the development of this antenna, such as monopoles [6], dipoles [7], and patch antennas [8]. This electrically steerable parasitic array radiator antenna consists of one active element and parasitic elements which are used to adjust beam direction. In [9], the authors presented active antenna tracking with directional antennas (DAs) for a networked robotic system design. This tracking system utilized weighted centroid algorithm and direction-of-arrival (DOA) estimation approach to achieve best quality between a mobile robot and a command center. The authors also examined the directionality of the radiation pattern with a stand-alone DA for DOA estimation. A customized DA with an actuated reflector for estimation of DOA of radio signal was described in [10]. In addition, a Medium Access Control (MAC) protocol that exploits the characteristics of DAs was presented in [11].

Broadcasting of information in a system of moving agents equipped with omnidirectional and DAs was investigated in [12]. The authors reported three important observations, namely: i) DAs perform better than omnidirectional antennas, ii) DAs whose beam-width is narrower perform even better, and iii) the performance enhances if DAs rotate. The formulation of the maximum flow problem in wireless sensor networks with switched beam DAs constrained by interference as an optimization problem was presented in [13]. The solution of this linear programming centralized problem determines the maximum flow. A compact switched-beam antenna was investigated in [14], which is composed of a four-

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element antenna array and shows eight directional patterns and an omnidirectional one; thereby ensuring a uniform coverage of the 360 degree horizon. Moreover, the authors in [15] constructed a reconfigurable angular diversity antenna with quad corner reflector arrays and a switching control. The design and development of a switched beam antenna at 2.45 GHz industrial, scientific and medical (ISM) band for wireless sensor network applications was presented in [16]. In [17], the authors presented a reconfigurable beam-steering antenna for wireless sensor network applications in the ISM band. Likewise, in [18], the authors used a beam steering antenna scheme for establishing multicast communication between millimeter-wave devices in 60 GHz wireless networks. Simulation results show that dynamic beam steering enables more efficient sectoring steering than fixed beam steering. The working principle of an electrically driven elliptical slit antenna, which is a directive, low-energy, electrical micro-source of light beams emitting in controlled directions was introduced in [19].

A 2-D beam forming system was developed in [20] based on 16 sub-array antennas. The beam forming function generates a high direction radiation pattern toward a mobile user. This enhances the receiver signal-to-noise ratio and channel capacity. In [21], the authors designed a dipole antenna using the HFSS (high-frequency structure simulator) software. The simulation results show better impedance, directivity, and gain. Moreover, the authors in [22] extended the use of the SPIDA (Swedish Institute of Computer Science Parasitic Interference Directional Antennas). This research shows that multiple directors elements result in improved performance in terms of maximum gain, narrower half power beam-width, and a lower module of the input port voltage reflection coefficient parameter. In [23], the authors designed and fabricated a single-layer 4×4 and 8×8 Butler matrices for multi-beam antennas. The experimental results compared favorably with the theoretical forecast. Planar beam steerable array antenna with dual-control circuits for feeding and reactive loadings was presented in [24]. This antenna system consists of four-way switchable beams implemented on a planar substrate and evaluated for orthogonal four-way beam steering performance. The new antenna system can radiate four orthogonal beams by switching an excited active element and the roles of parasitic antenna elements from reflectors to directors and vice versa. In [25], the authors designed a smart beam steerable array antennas based on branch-line hybrid coupler. This series fed array antenna can produce radiation patterns that can be changed to different beam for reducing the existing interference. Furthermore, dual-band sensor-antenna was designed in [26] for low energy consumption WSNs. Unlike the architecture of conventional wireless sensor nodes, the new approach in this paper does not require any processor device that consumes power. An investigation of the network connectivity of wireless networks with DAs was conducted in [27]. The paper presented a new analytical DA model called the *iris* model, to balance the accuracy against the complexity. In addition to the papers cited above, a four switchable BA dedicated to wireless sensor network nodes in the 2.4 GHz ISM band was presented in [28]. It consists of two fed monopoles and two loaded parasitic elements.

In an interesting contribution, the authors in [29] presented an energy-efficient medium access control (MAC) protocol using DAs in IEEE 802.11-based wireless sensor networks. This MAC protocol includes a new methodology for estimating effective DV for MAC sub-layer frames. The authors concluded that this new MAC protocol will further improve energy efficiency by reducing interferences from neighboring sensor nodes in the directional coverage areas of receiver sensor node. In another interesting contribution [30], the authors investigated the use of a mobile sink equipped with DAs to improve energy efficiency in wireless sensor networks. This research resolved three major concerns associated with leading efforts in the literature on improving energy efficiency in wireless sensor networks using a mobile sink fitted with DAs. The authors concluded that i) packets loss due to the continuous directional motion of mobile sink is eliminated as mobile sink can temporarily stop and receive packets from sensor nodes within its communication range at each instance of start/stop; ii) energy is conserved since the DAs are turned-off while the mobile sink is transiting from the current to the next start/stop points along its movement trajectory; and iii) mobile sink is able to completely scan its neighborhood using the four DAs at each instance of temporary stoppage.

In this current paper, the authors investigate a major concern associated with signal transmission and reception between WSNs. The research is based on WSNs equipped with switchable BAs system with orthogonal beam directions, in which each BA is capable of adjusting its initial operational time based on the current DV for the remaining packet(s) transmission (or reception). The operation of the BAs system is modelled by SMDP in which the sojourn time in each state of this SMDP model is allowed to change in relation to the DV of the current packet being transmitted (or received). It is noted that re-transmission of lost packet(s) will normally affect the initial estimated duration for data transfer between two communicating WSNs at any point in time. Moreover, it is important to note that retransmissions will lead to additional energy consumption. This paper also presents methodology for selectively switching each BA from non-operational to operational states, based on the strength of the received signal power. SMDP is a stochastic process which makes transition between states at decision epochs such that the amount of time spent in a state before moving to another state is random. To be specific, the time spent in each state before transiting to another state is called *sojourn time*, and it is exponentially distributed.

The rest of this paper is organized as follows. Motivation, problem formulation, and the BAs system model are presented in Section II. Numerical analysis and results are presented in Section III. Results obtained

are discussed in Section IV, while Section V summarizes and concludes this paper.

II. Motivation, Problem Formulation, and Beam Antennas System Model

Motivation for this research is discussed in Section II A, while problem formulation and the BAs system model are presented in Section II B.

A. Motivation for the Research

The greater radio frequency (RF) energy is focused in one direction, the greater gain is achieved in that particular direction. Multipath propagation, resulting from different versions of the same signal that have travelled from the transmitter to the receiver through different paths, may give rise to interference in diverse ways including multipath fading and signal distortion, and may result in loss of data. For the IEEE 802.11-based WSNs, such loss data must be re-transmitted. Clearly, re-transmission means that the initial estimated duration for transmission (or reception) will change in real-time; consequently affecting the time spent by an operational BA for transmission (or reception). Hence, the research for this paper is indeed necessary to resolve this major concern.

B. Problem Formulation and Beam Antennas System Model

The BAs system is an array antenna consisting of N elements. For the purpose of design and analysis in this paper, N is set equal to four; corresponding to four orthogonal beam directions. These four elements correspond to four BAs, but only one BA is activated to receive (or transmit) packet(s) at any given point in time, depending on the received signal power. It is noted that this array antennas system design consists of arrangement of antenna elements with a feed network. The transmitting antenna system is described as a Thevenin source consisting of a voltage generator (V_g) and series impedance (Z_g), delivering power (P_t) to the transmitting antenna; while the receiving antenna system intercepts section of the incidence wave, and subsequently delivers received power (P_r) to the load having impedance (Z_L).

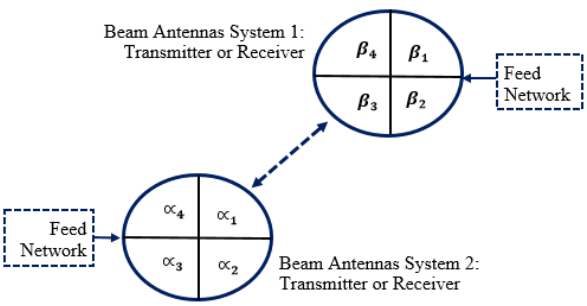

Fig. 1. Wireless sensor nodes equipped with 4-element beam antennas system with a feed network.

Fig. 1 shows the block diagram for the WSNs equipped with 4-element BAs system with a feed network. The four BAs labeled α_1, α_2, α_3, and α_4, or β_1, β_2, β_3, and β_4, individually provides 90 degrees azimuthal coverage, and are co-joined to form a BAs system that provides 360 degrees coverage.

The algorithm for selecting an operational BA and the SMDP model is presented below. This algorithm outlines the operational sequence of the BAs system.

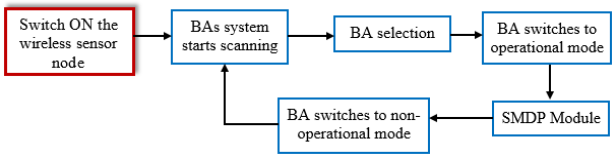

Fig. 2. System blocks for the BAs system scanning and operational cycling.

1) Algorithm

Step 1: Begin. Turn ON the WSN. All BAs are in non-operational state.

Step 2: Start the scanning cycle. For example, switch a BA (α_1, or β_3) to scanning mode. For a given scanning cycle, the four BAs start scanning one after the other.

Step 3: The operational BA selection is based on the strength of the signal power received by each BA. The antenna system selects the BA that received the greatest signal power.

Step 4: The antenna system then switches the selected BA from non-operational to operational state (or mode) for signal reception. During this transmission (or reception) phase, the remaining three BAs must remain in non-operational mode (or state).

Step 5: Upon selecting a particular BA for packets transmission (or reception), the SMDP module manages the packets reception (or transmission) phase by ensuring that the sojourn time is changeable in real-time, if necessary.

Step 6: At the end of transmission (or reception) phase, the WSN's antenna system switches the BA from operational to non-operational state, and the system's process returns to Step 2.

Step 7: End.

The system block diagram for the BAs system scanning and operational cycling is presented in Fig. 2.

It is noted that the WSN operates in an infinite horizon; thus it is expected that the BAs system would run continuously over a long time. The convergence of an infinite SMDP-based system process was proved in [30].

2) Selection of an operational BA

Selection of an operational BA at any given point in time involves comparing the power of the signal (in dB) received by the BAs, to determine the BA with the greatest received signal power. That is, compute

$$P_{\mathrm{dB}_{(\mathrm{BA}_i)}} = 10\log_{10}\left((\text{ratio of powers})_{(\mathrm{BA}_i)}\right) \tag{1}$$

where i ranges from 1 to 4, and $P_{\mathrm{dB}_{(\mathrm{BA}_i)}}$ denotes signal power received (in dB) for each BA. Thereafter, the BAs system selects the BA with the greatest received signal power (P_{dB}).

It is noted in items (i), (ii), (iii), and (iv) below that $\begin{bmatrix} x_1 & x_2 & x_3 & x_4 \end{bmatrix}$, $[\cdots]_{4\times4}$, and $\begin{bmatrix} y_1 & y_2 & y_3 & y_4 \end{bmatrix}$, represents

the input matrix, BAs matrix, and selected operational BA matrix (output matrix), respectively. Based on the maximum signal power received, the matrix-based BA selection (or switching) methodology is presented as follows.

(i). *BA #1 selection*: The BA #1 is selected (e.g., sector α_1 in Fig. 1) and switched from non-operational to operational mode, while the other three BAs must remain in non-operational mode.

$$\begin{bmatrix}1 & 0 & 0 & 0\end{bmatrix}\begin{bmatrix}\alpha_1 & 0 & 0 & 0\\ 0 & \alpha_2 & 0 & 0\\ 0 & 0 & \alpha_3 & 0\\ 0 & 0 & 0 & \alpha_4\end{bmatrix}=\begin{bmatrix}\alpha_1 & 0 & 0 & 0\end{bmatrix}$$

(ii). *BA #2 selection:* The BA #2 is selected (e.g. sector α_2 in Fig. 1) and switched from non-operational to operational mode, while the other three BAs must remain in non-operational mode.

$$\begin{bmatrix}0 & 1 & 0 & 0\end{bmatrix}\begin{bmatrix}\alpha_1 & 0 & 0 & 0\\ 0 & \alpha_2 & 0 & 0\\ 0 & 0 & \alpha_3 & 0\\ 0 & 0 & 0 & \alpha_4\end{bmatrix}=\begin{bmatrix}0 & \alpha_2 & 0 & 0\end{bmatrix}$$

(iii). *BA #3 selection:* The BA #3 is selected (e.g. sector α_3 in Fig. 1) and switched from non-operational to operational mode, while the other three BAs must remain in non-operational mode.

$$\begin{bmatrix}0 & 0 & 1 & 0\end{bmatrix}\begin{bmatrix}\alpha_1 & 0 & 0 & 0\\ 0 & \alpha_2 & 0 & 0\\ 0 & 0 & \alpha_3 & 0\\ 0 & 0 & 0 & \alpha_4\end{bmatrix}=\begin{bmatrix}0 & 0 & \alpha_3 & 0\end{bmatrix}$$

(iv). *BA #4 selection:* The BA #4 is selected (e.g. sector α_4 in Fig. 1) and switched from non-operational to operational mode, while the other three BAs must remain in non-operational mode.

$$\begin{bmatrix}0 & 0 & 0 & 1\end{bmatrix}\begin{bmatrix}\alpha_1 & 0 & 0 & 0\\ 0 & \alpha_2 & 0 & 0\\ 0 & 0 & \alpha_3 & 0\\ 0 & 0 & 0 & \alpha_4\end{bmatrix}=\begin{bmatrix}0 & 0 & 0 & \alpha_4\end{bmatrix}$$

Table I summarizes the output of the four elements BAs selection (or switching) system.

TABLE I: BAS SYSTEM SWITCHING

Greatest received signal power (Fig. 1)				Selected Operational BA
α_1 (or β_1)	α_2 (or β_2)	α_3 (or β_3)	α_4 (or β_4)	
1	0	0	0	#1
0	1	0	0	#2
0	0	1	0	#3
0	0	0	1	#4

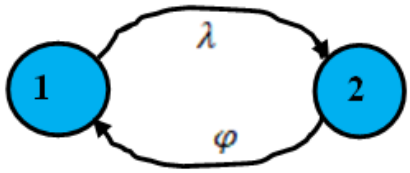

Fig. 3. Transition rate diagram for states of the beam antennas system.

3) Semi-Markov Decision Process (SMDP) model

Markov process can be formulated from the system's cost or reward standpoint. The operation of the BAs system is characterized by SMDP, which normally consists of five components, namely: decision epochs, states space, action space, transition probability, and rewards, and is described mathematically [31] as follows.

$$\text{SMDP}=\{T,S,A,h(x|s,a),z(s,a)\} \tag{2}$$

where $t\in T$, $s\in S$, $x\in S$, and $a\in A$. In addition, T, S, A, $h(x|s, a)$, and $z(s, a)$ represents decision epochs, state space, action space, transition probability, and rewards, respectively.

The SMDP model for the operation of the BAs system is described as follows. *Decision epochs*: points in time $(t_1,t_2,\cdots,t_\infty)$ when the BAs system takes action; *states*: s_1(non-operational), and s_2 (operational); *action space*: transmit or receive; *transition probability*: given that an action a is chosen in current state s at current decision epoch t, the BA's system state x at the next decision epoch is determined by the probability distribution $h(x|s, a)$ and *reward*: the immediate discounted reward function $z(s, a)$ Allowable actions in states are defined as $A=\{a_{j,k},a_{k,j}\}$, where $j\neq k$ The transition rate diagram for the states of the BAs system is shown in Fig. 3, where λ and φ, represents constant rate parameters. It is noted that State 1 and State 2 denote non-operational and operational states, respectively.

The immediate discounted reward function ([30], [31]) in a state $s\in S$, with action $a\in A$, is given by

$$z(s,a)=l(s,a)\int_0^\infty\sum_{x\in S}\left[\int_0^\sigma e^{-\gamma t}d(x,s,a)h(x\,|\,t,s,a)dt\right]G(d\sigma\,|\,s,a) \tag{3}$$

where γ denotes the discount rate, $G(\sigma\,|\,s,a)$ is defined as the probability that the next decision epoch occurs within σ time units given that action a is chosen in State s at the current decision epoch. The immediate reward, $z(s, a)$, received in a current state consists of the lump sum reward $l(s, a)$ and accumulated rewards at continuous reward rates $d(x, s, a)$ between decision epochs. In the SMDP model, the natural process $h(x|t, s, a)$ does not change state until the next decision epoch; therefore, $h(x|t, s, a)$ in (3) is set equal to 1.

To calculate the immediate discounted reward, there is a need to evaluate the double integrals in (3):

$$\int_0^\infty\int_0^\sigma e^{-\gamma t}dt\,G(\sigma\,|\,s,a)\,d\sigma$$

This yields

$$E_{\text{dint}} = \frac{1}{\gamma}(*)\left\{\beta_t + \frac{1}{\gamma}\left(e^{-\gamma\beta_t} - 1\right)\right\} \quad (4)$$

where (*) represents the value for $G(\sigma|s, a)$ in the current state, β_t is the sojourn time, and E_{dint} denotes the result of the evaluation of the double integrals. The values for the discount rate γ and sojourn time distribution probability (i.e. $G(\sigma|s, a)$) are provided in each state.

For the next state $x \in S$, and current state $s \in S$, the discounted transition function ([30], [31]) is defined as

$$w(x|s,a) = \int_0^\infty e^{-\gamma t} R(dt, x|s,a) \quad (5)$$

where dt denotes time-differential, while $R(t, x|s, a)$ is the joint probability that the state at the next decision epoch equals x, and the next decision epoch occurs at (or before) time t when action a is chosen in State s at current decision epoch.

$$R(t, x|s,a) = H(x|s,a)G(t|s,a) \quad (6)$$

where $H(x|s, a)$ denotes transition probability of the embedded MDP (Markov decision process) in the SMDP, which essentially describes evolution of the BAs system at decision epochs only.

To address the need for extended transmission (or reception) time for an operational BA, the sojourn time indefinite integral equation:

$$\int_0^\infty e^{-\gamma t} G(dt \mid s,a)$$

is re-written and the upper limit of this integral equation is associated with the received DV of the current packet as follows:

$$T_{\text{available}} = \int_0^\infty \left(e^{-\gamma t} dt\right) G(t|s,a) = \lim_{m\to\infty}\left\{\int_0^{m=DV} \left(e^{-\gamma t}\right) G(dt|s,a)\right\} \quad (7)$$

where $T_{\text{available}}$ denotes the availability time of the operational BA, which in this case is the prevailing sojourn time. The approach in (7) was used for the indefinite integral in (3) to obtain the solution in (4). The DV in (7) denotes the DV of the current packet being transmitted (or received). For situation in which re-transmission of packet(s) becomes necessary, the effective DV of the current packet would be an extended time; thereby causing the transmitter (or receiver) WSN to accordingly adjust the availability time of its operational BA.

In calculating the discounted state transition function, the single integral function was evaluated as follows:

$$E_{\text{sint}} = w(x|s,a) = (+)\int_0^\infty e^{-\gamma t}(**)dt \quad (8)$$

where (+) and (**) denote $H(x|s, a)$ and $G(t|s, a)$ respectively; and E_{sint} is the result of the evaluation of the single integral. Subsequently, equation (8) yields

$$E_{\text{sint}} = (+)(**)\left(\frac{1}{\gamma}\right)\left\{1 - e^{-\gamma\epsilon}\right\} \quad (9)$$

where ϵ represents corresponding value of the sojourn time.

The optimality equation for this discounted SMDP model ([30], [31]) is given by

$$v(s) = \max_{a\in A}\left\{z(s,a) + \sum_{x\in S} w(x|s,a)v(x)\right\} \quad (10)$$

where $v(x)$ denotes the sum of discounted rewards of the system starting from next state x, while $v(s)$ represents the sum of discounted rewards of the system starting from current state s.

TABLE II: NUMERICAL PARAMETERS

Description	Values
Number of beam antennas	4
States (operational; non-operational)	2
Rewards (lump sum in operational state); $l(s, a)$	10 dB (=10)
Rewards (continuous reward rate in operational state); $d(x, s, a)$	15 dB (=31.6)
Cost (lump sum in non-operational state); $l(s, a)$	-5 dB (=0.32)
Cost (continuous cost rate in non-operational state); $d(x, s, a)$	-3 dB (=0.5)
Initial estimated duration for packets transmission or reception (in seconds)	60
Transition probability at decision epochs: $H(s_2\|s_1, a)$; $H(s_1\|s_2, a)$	0.90; 0.1
Discount rate (γ)	0.1

The optimal policy is a decision that selects the alternative that yields the maximum total of sum of discounted rewards in current states. Equations (3), (4), (7)-(10) above, are the basis for the optimal analysis, which is implemented in the MATLAB software using the numerical values presented in Table II.

With respect to the numerical values presented in Table II, the number of BAs is equal to four; any other value will require a change to the dimension of the BAs system's switching (or selection) matrices in Section II. Moreover, the BAs system's states are two, since the BAs system can either be switched ON or OFF. Reward and cost values are chosen based on the fact that reward indicates gain (+) while cost indicates loss (–). In addition, sojourn time adjustment is based on the initial estimated duration for packets transmission (or reception) which in this paper is chosen as 60 seconds (any other initial values are usable for the sojourn time adjustment). The transition probability of 0.9 or 0.1, indicates probability of transiting from current state to a next state or remaining in same state, respectively. Other probability values used produced corresponding changes in values of $v_1(s)$ and $v_2(s)$ for both Options A and B. Moreover, the optimal analysis (Table III) was based on a discount rate (γ) of 10%; other lower discount rates (e.g. 5% or 1%) yielded larger values for both Options A and B.

III. Numerical Analysis and Results

For the purpose of illustration in this paper, the unit of reward and cost is decibel (dB), which is converted to the corresponding values using, value= $10^{x_{(db)}/10}$. The computed values presented in Table III are assumed to represent bytes received (or transmitted) by WSN equipped with BAs.

The optimal analysis in the SMDP model for the operation of the BAs system involves calculating the total of sum of discounted rewards in current states. For this analysis, the initial sojourn time (ST) for an operational BA is 60 seconds, while the sojourn time adjustments (increments) ranges from 10% to 80% of the sojourn time. This sojourn time adjustments represent changes to the initial sojourn time, to accommodate the extra time needed for re-transmissions. It is important to note that sojourn time in the SMDP model translates to the operational time of an operational BA.

Table III: Optimal Analysis (Based on Total of Sum of Discounted Rewards from States 1 and 2).

(X)	(Y)	States / Options	Sojourn time (ST) adjustment (in sec.)	Sum of discounted rewards of the BAs system in states		Total	Maximum
				1	2		
1	$v_1(s)$	A	Initial ST	300,000	1,300	301,300	361,500
		B	1.1 × Initial ST	360,000	1,500	361,500	
1	$v_2(s)$	A	Initial ST		1,300	1,300	1,500
		B	1.1 × Initial ST		1,500	1,500	
2	$v_1(s)$	A	Initial ST	300,000	1,300	301,300	431,700
		B	1.2 × Initial ST	430,000	1,700	431,700	
2	$v_2(s)$	A	Initial ST		1,300	1,300	1,700
		B	1.2 × Initial ST		1,700	1,700	
3	$v_1(s)$	A	Initial ST	300,000	1,300	301,300	512,000
		B	1.3 × Initial ST	510,000	2,000	512,000	
3	$v_2(s)$	A	Initial ST		1,300	1,300	2,000
		B	1.3 × Initial ST		2,000	2,000	
4	$v_1(s)$	A	Initial ST	300,000	1,300	301,300	592,300
		B	1.4 × Initial ST	590,000	2,300	592,300	
4	$v_2(s)$	A	Initial ST		1,300	1,300	2,300
		B	1.4 × Initial ST		2,300	2,300	
5	$v_1(s)$	A	Initial ST	300,000	1,300	301,300	672,600
		B	1.5 × Initial ST	670,000	2,600	672,600	
5	$v_2(s)$	A	Initial ST		1,300	1,300	2,600
		B	1.5 × Initial ST		2,600	2,600	
6	$v_1(s)$	A	Initial ST	300,000	1,300	301,300	762,900
		B	1.6 × Initial ST	760,00	2,900	762,900	
6	$v_2(s)$	A	Initial ST		1,300	1,300	2,900
		B	1.6 × Initial ST		2,900	2,900	
7	$v_1(s)$	A	Initial ST	300,000	1,300	301,300	863,200
		B	1.7 × Initial ST	860,000	3,200	863,200	
7	$v_2(s)$	A	Initial ST		1,300	1,300	3,200
		B	1.7 × Initial ST		3,200	3,200	
8	$v_1(s)$	A	Initial ST	300,000	1,300	301,300	963,500
		B	1.8 × Initial ST	960,000	3,500	963,500	
8	$v_2(s)$	A	Initial ST		1,300	1,300	3,500
		B	1.8 × Initial ST		3,500	3,500	

The results of the optimal analysis (in Table III) are obtained using (10), where the immediate discounted reward function, $z(s, a)$, is computed using (3) and (4), while the discounted transition function, $w(s, a)$ is computed using (7), (8) and (9). Column X and Column Y of Table III denotes decision epochs and current states in the SMDP model, respectively. As shown in this table, each adjustment of the sojourn time yields a different sum of discounted rewards. For example, whereas initial sojourn time of 60 seconds yields total of sum of discounted rewards of 301,300 bytes starting from State 1 for Option A, a 10% increase in the sojourn time yields 361,500 bytes for Option B.

The results for total of sum of discounted rewards starting from State 1 (in Table III) for Option A and Option B at decision epochs are presented graphically in Fig. 4. Similarly, Fig. 5 shows the results for total of sum of discounted rewards starting from State 2 for Option A

and Option B at decision epochs. In Fig. 4 and Fig. 5, the solid line represents Option A, which is the case in the existing literature in which WSN equipped with BAs does not possess capability to dynamically adjust the operational BA's sojourn time in real-time. The dashed line represents Option B, the approach presented in this paper wherein the WSN uses the DV in current packets to adjust the initial estimated sojourn time of the operational BAs.

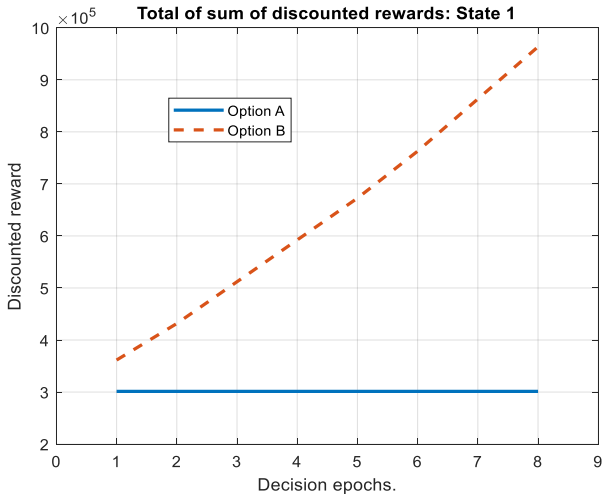

Fig. 4. Total of sum of discounted rewards in states: Starting from State 1.

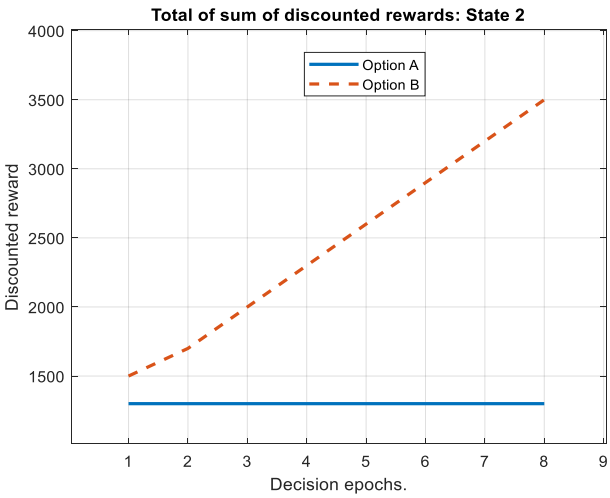

Fig. 5. Total of sum of discounted rewards in states: Starting from State 2.

IV. Discussion of Results

Recall from Section II B, Step 5 and Step 6 of the algorithm, that the BA's sojourn time corresponds to the reception (or transmission) phase of an operational BA. In Table III, Fig. 4 and Fig. 5, Option A represents the case in the existing literature in which WSN equipped with BAs does not possess capability to dynamically adjust operational BA's sojourn time. For this case, the BA's sojourn time is based on the initial estimated DV for packets reception (or transmission). Option B is the approach presented in this paper in which the WSN equipped with BAs system uses the DV in current packets to adjust the initial estimated sojourn time of an operational BAs. Whereas Fig. 4 shows the total of sum of discounted rewards in current states starting from State 1 for Option A and Option B, Fig. 5 shows the total of sum of discounted rewards in current states starting from State 2 for Option A and Option B. The initial duration for packet reception (or transmission) is 60 seconds (Table III). Different sojourn time adjustments are subsequently effected as follows: i) 1.1 *times* initial sojourn time; ii) 1.2 *times* initial sojourn time; iii) 1.3 *times* initial sojourn time; iv) 1.4 *times* initial sojourn time; v) 1.5 *times* initial sojourn time; vi) 1.6 *times* initial sojourn time; vii) 1.7 *times* initial sojourn time; and viii) 1.8 *times* initial sojourn time.

Fig. 4 shows that Option B (dashed line) yields the optimal results at all decision epochs for the case when the BAs system's process starts from State 1. Similarly, Fig. 5 shows that Option B produces the optimal results at all decision epochs for the case when the BAs system's process starts from State 2. At decision epoch 2 in Fig. 4 (for example) when the sojourn time is adjusted by 1.2 of the initial DV (i.e., aggregate of 72 seconds), Option A (solid line) yields total of sum of discounted rewards of 301,300 bytes, while Option B yields 431,700 bytes. For this case, adopting Option A will result in a loss of 130,400 bytes since the operational BA would have switched from operational state to non-operational state prior to the completion of packets reception based on the initial DV of 60 seconds. The optimal decision therefore is to select Option B, which extends the sojourn time to 72 seconds, thereby completely receiving (or transmitting) total of 431,700 bytes. Similarly, at decision epoch 2 in Fig. 5 (for example) when the sojourn time is adjusted by 1.2 of the initial DV (i.e., total time of 72 seconds), Option A (solid line) yields total of sum of discounted rewards of 1,300 bytes, while Option B (dashed line) yields 1,700 bytes. In this case also, adopting Option A will result in a loss of 400 bytes. The optimal decision therefore is to select Option B.

In summary, the results obtained from the optimal analysis show the following:

a) The ability to adjust the upper limit value in the sojourn time equation (i.e., Equation (7)), enables the WSN equipped with BAs system to extend the availability time of an operational BA in relation to the DV of current packet being transmitted (or received).
b) Extending the sojourn time as needed in real-time, enables the WSN to retain its operational BAs in receive (or transmit) mode for the entire duration of packets reception (or transmission).
c) The results presented in Table III, Fig. 4 and Fig. 5, are consistent with the statements (a) and (b) above, since Option B yields the optimal results.

Unlike the other solutions previously cited, for example [26], the approach in this current paper requires the sensor node to have processor element to execute the algorithm.

The main contributions of this research are summarized as follows:

1) The capability to adjust the upper limit value in the sojourn time equation (i.e., equation (7)) enables IEEE802.11-compliant WSNs equipped with the BAs system to extend the availability time of its operational BA in relation to the DV of current packet being transmitted (or received). The authors found no paper(s) in the existing literature that provides this capability.
2) In addition, unlike the other research previously cited (for example [28]), the approach in this paper presents BAs system design and also the algorithm to manage transmit and receive operations by WSNs.
3) Communication is the most important power-consuming function of WSNs. To achieve energy-efficient communication and increase the life span of WSNs, it is important that retransmissions of incomplete packets reception are significantly reduced. The research results presented in this paper provide promising solution to the problem of energy-inefficient communications, by ensuring that the BAs remains in operational state for the entire duration of communication between transmitting and receiving WSNs.

V. Summary and Conclusion

This paper presented a four-element switchable BAs system, in which the operation of the BAs was characterized by SMDP with variable sojourn time. In addition, a matrix-based switching methodology was presented for selecting an operational BA based on the received signal power by each BA. Upon selecting a particular BA for packets reception (or transmission), the SMDP module manages the packets reception (or transmission) phase by ensuring that the sojourn time is changeable in real-time, if necessary. Optimal analysis was carried out to obtain optimal results in terms of the maximum total of sum of discounted reward in current states. The results obtained show the following: i) adjusting the upper limit value in the sojourn time equation enables the WSN equipped with BAs system to extend the operational time of its operational BA (in real-time) based on DV of current packet being received (or transmitted); and ii) extending the sojourn time as needed enables the WSN to retain its operational BA in receive (or transmit) state for the entire duration of packets transmission (or reception). The efficacy of this switchable BAs system with variable sojourn time was tested via numerical analysis implemented in MATLAB software.

In conclusion, the results show that this novel approach enables the WSNs equipped with BAs to select and maintain an operational BA with greatest received signal power in receive (or transmit) mode for the entire duration of packets reception (or transmission). The authors found no paper in the existing literature that provides this capability.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Abayomi Ajofoyinbo conducted the research, developed the theoretical formulation, performed the numerical calculations, and wrote the manuscript with input from the co-authors. David Olowokere and Oye Ibidapo-Obe provided very useful feedback that helped to shape the research, analysis and the manuscript. All authors approved the final version of the manuscript.

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