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A Smart Game for Data Transmission and Energy Consumption in the Internet of Things

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***Abstract*—The current trend in developing smart technology for the Internet of Things (IoT) has motivated a lot of research interest in optimising data transmission or minimising energy consumption, but with little evidence of proposals for achieving both objectives in a single model. Using the concept of game theory, we develop a new MAC protocol for IEEE 802.15.4 and IoT networks in which we formulate a novel expression for the players' utility function and establish a stable Nash Equilibrium (NE) for the game.**

The proposed IEEE 802.15.4 MAC protocol is modelled as a smart game in which analytical expressions are derived for channel access probability, data transmission probability and energy used. These analytical expressions are used in formulating an Optimization Problem (OP) that maximizes data transmission and minimizes energy consumption by nodes. The analysis and simulation results suggest that the proposed scheme is scalable and achieves better performance in terms of data transmission, energy efficiency and longevity, when compared with the default IEEE 802.15.4 access mechanism.

***Index Terms*—IEEE 802.15.4, MAC, Game Theory, IoT, Optimization, Energy Aware.**

I. INTRODUCTION

In a recent publication [1], the authors trace the idea of a smart city to an academic paper written in 1993 which introduced the concept of an intelligent city. The concept has generated considerable interest, particularly in recent years, with the emergence of the Internet of Things (IoT) and the subsequent proliferation of smart devices [2]–[4]. The main aim of IoT is to integrate everyday objects into the virtual world of information technology and make them proactive actors of the Internet. The major challenge facing this vision lies in building large-scale autonomous, low cost, low energy wireless sensory networks that will interact with Internet objects and cloud services.

The requirements for connectivity and environmental considerations show that IoT devices need to be smart, both in terms of connectivity and energy usage. It follows that in addition to the wide interest in the ongoing interconnectivity of devices in IoT, the cognitive behaviour of IoT devices is another prevailing area of interest [5]–[10]. The work in [11] and [12] address this concept of cognitive Internet of Things by suggesting that IoT devices should be "intelligent" enough to be able to adapt themselves to various scenarios and situations they may encounter in their communication process and respond to them 'cleverly'. This includes their ability to achieve transmission efficiency which constitutes a trade-off between data transmission and energy conservation. We refer to this 'clever' behaviour as cognitive which is a product of smartness.

The IEEE 802.15.4 standard, by virtue of its features, is one of the most favoured media access control (MAC) protocols for the implementation of IoT. The IEEE 802.15.4 devices are inherently resource-constrained with limited computational power, limited memory size, short communication and sensing range, and limited energy since they are battery powered. However, the process of packet transmission in wireless networks requires the use of energy, hence a node increases its data transmission at the expense of its energy. Consequently, one of the most important goals of the IEEE 802.15.4 standard and IoT networks is to prolong the battery life of devices by reducing their energy usage. Therefore, on one hand, the main design goal of a typical MAC protocol is to provide high throughput in terms of data transmission and some degree of quality of service (QoS) [13]. On the other hand, wireless MAC protocol ought to give higher priority to minimising energy consumption than maximizing throughput and QoS since data transmission is subject to the available energy on the device. The more throughput a device needs to achieve, the more energy it needs to use. This constitutes an area of challenge for low energy networks like IEEE 802.15.4 and the IoT in which there are requirements for throughput as well as energy efficiency.

In addition, the requirement to save energy is also significant in an environment in which selfish nodes are allowed to operate since part of the energy is wasted in retransmission of lost packets. There is therefore a need to strike a balance between the two opposing requirements: using energy for immediate transmission and saving energy for future transmission. Consequently, the new generation of smart devices are faced with the challenge of maintaining unlimited connectivity with limited energy. In order to satisfy both requirements for data throughput and energy conservation, and thus, achieve transmission efficiency in IEEE 802.15.4 and IoT networks, we present a smart game approach to the MAC protocol, in which IEEE 802.15.4 devices can optimize their data throughput and energy consumption. Our scheme is designed to combine data throughput features with energy saving mechanisms in resource-constrained devices. The analysis and evaluation of our scheme suggests an improvement in transmission efficiency. Thus, it has the potential of enhancing the IEEE 802.15.4 standard and IoT devices with additional features such as energy awareness and longevity, whilst maintaining good data throughput.

A. Motivation

The current trend of developing smart technology as observed in [2] and [4] is the first motivation factor for this proposal of a smart MAC protocol. We regard as an ambitious goal, the process of equipping IoT devices with sufficient

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intelligence at the MAC layer to enable them to communicate effectively and efficiently by evaluating the potential risks that may be associated with the process of communicating with other devices and mitigating such risk seamlessly.

Considerable research has been carried out in data throughput improvement or energy efficiency in IEEE 802.15.4 and IoT networks [14]–[31]. However, very little consideration has been given to one solution that combines both features. This need for a trade-off between data transmission and energy consumption in IoT devices is another motivating factor for this work.

In addition to the requirements for a smart MAC protocol with cognitive behaviour and transmission efficiency in IoT networks as explained above, the green initiatives for environmental consideration implies that IoT devices ought to be smart in terms of energy conservation as discussed in [9], [30]–[36]. That is, they are to minimise energy used in order to preserve the environment. This need for low energy (i.e. green) IoT devices in order to preserve the environment is an additional motivation for our work.

B. Related Work

The requirement for data transmission and energy efficiency in constrained IoT devices has motivated a lot of literature in protocol design. These works can be divided into two main categories. The first thread of literature is concerned with improving throughput while the second approach is about improving energy efficiency of IoT devices. The works in [14]–[24] are all related to our work in the sense that they all use one mechanism or another to improve data transmission. However, the works in [25]–[31], [37] all belong to the second thread, they are designed to improve energy efficiency for wireless devices.

All the above stated works seem to choose one of the two attributes: energy efficiency or data throughput and try to get the best out of it with the intention that the other attribute will also be optimised in the process. However, a device does not necessarily achieve transmission efficiency by transmitting more data since this could be at the cost of excessive energy usage. The same principle can be similarly applied to energy efficiency. We observed that a node gains throughput by using part of its energy to transmit data as discussed in [15], [30], [31], [38], [39]. This implies that, using energy to gain immediate throughput and saving energy in order to gain throughput in the future are two sides of the same coin, hence they are to be considered together.

In this paper, we look at the problem from the perspective of a smart game in which all nodes are forward looking with the strategy to get the best of the two contrasting outcomes: data throughput and energy efficiency. To the best of our knowledge, the current IEEE 802.15.4 MAC protocol is not designed to make such cognitive decision or strike such a balance, neither does any current CSMA proposal include such optimisation. Consequently, the need for a transmission strategy that will balance the requirement for energy efficiency as discussed in [25]–[31], [37] with that of data throughput as discussed in [14]–[24] constitute a gap.

In addition to the works mentioned above, another work that is related to our work is [40], in which the authors present data centre choice of utility company and workload schedule as a many-to-one matching game in which each utility company could supply electricity to multiple data centres and a data centre could match with one utility company to save cost. They establish a stable condition for their game, in which no data centre has any incentive to change its matched utility company unilaterally.

Similarly the work in [41] is related to our work in the sense that it investigates how the energy consumption of a sensor node affects the longevity of WSN devices. The authors discuss the significance of energy-efficient routing protocols in prolonging the lifetime of WSN devices. The work address routing protocols design; hence, it is a layer 3 solution, while our work address MAC protocol design, thus, it is a layer 2 solution.

In addition to the works discussed above, a significant amount of literature such as [42]–[44] has been written on the game theoretic solution and interconnectivity of devices in IoT. However, designing a smart MAC protocol for IoT nodes, so that the IoT global network can progress from interconnectivity of devices on the Internet to interconnectivity of smart devices on the Internet is an ongoing area of research.

C. Contributions

In this work, our main contributions are as follows:

- A novel smart MAC protocol is proposed to maximize data transmission and minimize energy consumption in IoT devices. The proposed smart MAC protocol differs from the existing solutions by combining data transmission with energy efficiency features, for resource-constrained devices. To the best of our knowledge, the current IEEE 802.15.4 MAC protocol is not capable of such cognitive behaviour, neither does any current CSMA proposal include such optimisation.
- The derivation of new expressions for channel access probability, data transmission probability and energy used for IEEE 802.15.4 nodes and the formulation of a new probability centric utility expression which is based on cost benefit analysis (CBA), i.e data transmitted (the benefits) and the energy used to achieve it (the cost).
- The proposal of a new flexible CW mechanism for IEEE 802.15.4 in which all nodes within the same contention domain set a uniformly calculated (consensus) CW value rather than using the current constant value as defined in the default protocol. This consensus CW constitutes the optimal value and the stable state for the game. Consequently, we have established that it is better to make the CW a dynamic variable which is calculated and set by each node at run time, since this leads to a better performance in terms of transmission efficiency.
- The simulation results show performance improvements for the smart MAC model over the existing default model in terms of achieving better data transmission whilst minimising energy used. Consequently, it could lead to preservation of the environment as a result of the

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prolonged battery lifetime (longevity), hence leading to energy aware (i.e. green) IoT devices.

D. Organization

The rest of this paper is structured as follows. The proposed model is discussed in section 2 while the smart game formulation and analysis are illustrated in section 3. The game utility and solution are discussed in section 4 with the simulation and evaluation of the model presented in section 5. Finally, the conclusion and future work are discussed in section 6.

II. THE PROPOSED MODEL

A. The IEEE 802.15.4 Standard

The IEEE 802.15.4 standard is designed for low data rate, short distance transmission, and low power consumption applications in conformity with WSN constraints. The IEEE 802.15.4 MAC layer supports two operational modes: the non-beacon-enabled mode with unslotted Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) and the beacon-enabled mode in which beacons are periodically sent by the Personal Area Network Coordinator (PANC) to synchronize nodes and to specify superframe duration in which all transmissions must occur [45]. The beacon-enabled mode uses slotted CSMA/CA and Guaranteed Time Slot (GTS) while the non-beacon-enabled mode uses unslotted CSMA/CA only. The MAC layer controls access to the radio channel using the CSMA/CA mechanism. The work presented in this paper is limited to the beacon-enabled mode with slotted CSMA/CA only as result of time and space constraints.

The mechanism of beacon-enabled mode is based on superframe structure. A superframe structure is as shown in Fig. 1. It is bounded by two successive beacons and consists of an active portion and an optional inactive portion. The Beacon Interval (BI) defines the time between two successive beacons. The BI consists of the active duration known as Superframe Duration (SD) and the Inactive Period (IP), in which nodes can enter a low-power (sleep) mode. The active portion (SD), is also divided into Contention Access Period (CAP) and Contention Free Period (CFP) [39].

In the slotted CSMA-CA, the contention access process is influenced by three variables: Number of Backoff (NB), Contention Window (CW) and Backoff Exponent (BE). The NB represents the maximum backoff time allowed in one transmission attempt. The CW refers to the contention window size, which is the number of backoff period the channel must be clear of activity before transmission can commence. The CW is set at a default value of 2 in the standard. The BE determines the maximum backoff period a node should wait before attempting to access the channel by performing Clear Channel Assessment (CCA) . The maximum number of permitted random backoff stage is determined by the parameter macMaxCSMABackoffs, which has a default value of 5. All the nodes in the PAN synchronize their backoff boundaries to the superframe slot boundaries of the PANC as indicated by its beacons.

A device can transmit during the CAP by contending with other devices using slotted CSMA/CA. The CFP is optional

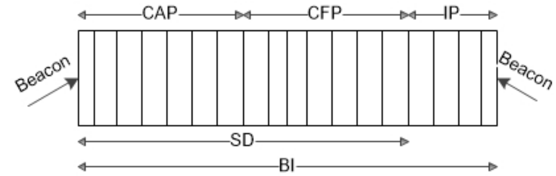

Fig. 1: IEEE 802.15.4 Super-frame Structure

and used for contention free communication for time sensitive transmission. The CFP is a duration in which a device with an allocated GTS can communicate without the need for CSMA/CA process. The PANC is responsible for the allocation of the GTS. A maximum of 7 slots can be reserved for contention free communication (GTS) out of a total 16 slots of the active portion.

B. Terminologies and Assumptions

A network node that can operate interactively and autonomously in an intelligent manner is regarded as smart devices and the automated intelligent interaction is refers to as smart or cognitive game. A game is regarded as cooperative if all players are motivate to cooperate through external enforcement or internal incentive in order to achieve the desire outcome for all players. However, if there is lack of motivation (either through external enforcement (deterrent) or internal incentive) to cooperate in order to achieve the desire outcome for all players, then the game is regarded as non-cooperative. Cognitive Utility refers to utility derived by cognitive nodes, while the symbols E_u and E_a represent nodes' energy used and available energy respectively.

In order to formulate our game, we assume the following:

- All players are rational, meaning they will not intentionally or wilfully play against their own interest.
- Each player can either cooperate or defect depending on their motivations.
- Each player could set their contention window size CW (w) independently either cooperatively or non-cooperatively.
- Each player knows their energy (battery) level and can independently determine their energy use and their available energy.
- In the default protocol, if the value of the parameter NB is greater than the parameter macMaxCSMABackoffs which has a default value of 5, the algorithm terminates in failure. However, in our model, we assume that each player can manipulate the protocol by setting the value of their macMaxCSMABackoffs to infinity to enable them to keep on trying until they succeed.
- Each node (player) can determine the numbers of other players in the game by listening to the shared channel.
- Each node (player) always has packets to transmit and will always contend for channel access.

C. The Smart Game Algorithm

The proposed smart game for MAC protocol maintains full compatibility with the default IEEE 802.15.4 CSMA in terms of information flow. However, the smart CSMA algorithm differs in the sense that each node determines the expected utility based on the number of perceived nodes n, its load and energy level. In its strategic state, each node evaluates data transmission probability and sets appropriate value for its contention window CW as explained in the game formulation section below. As shown in Fig. 2, each node start the CSMA algorithm by setting all parameters as in the default protocol. Then, each node performs CCAs and send its data if successful, otherwise the algorithm enters the smart mode which is the strategic state in which it determines the number of perceived nodes and set the optimum CW accordingly.

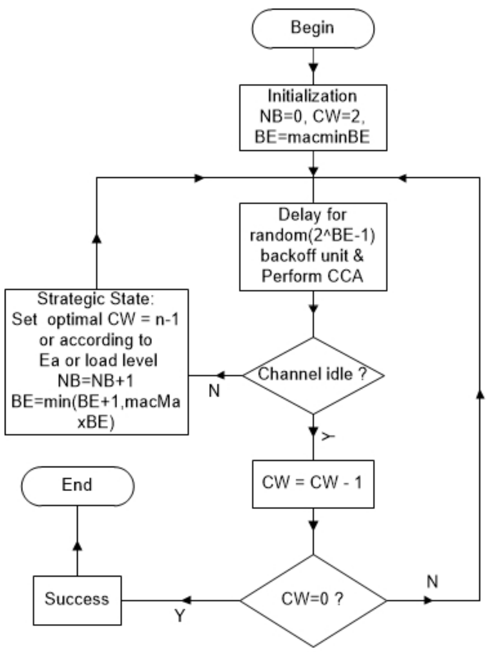

Fig. 2: Smart Game Flow Chart

Parameters Symbols	Descriptions
pl_i	player i
PL	set of players
s_i	strategy of pl_i
S	set of strategies
U	utility function
u_i	utility of pl_i
Γ	set of time
t_i	time at which pl_i take action s_i
D_i	data transmitted by pl_i
E_i	energy used by pl_i to transmit D_i
p_a	access probability of player i
p	prob. of successful data transmission of player i
$\eth_{mac}$	MAC game
w_i	CW of pl_i

TABLE I: Nomenclature Table-A

D. *Game Definition & Modelling*

A smart game model with n nodes representing a set of players is considered. The goal of each player in the game is to maximize its utility, which is defined as data transmitted (in bytes) per energy used (in joules) to achieve such transmission. The game is symbolized as follows:

$$\eth_{mac} = \Big\langle PL, S, U, \Gamma \Big\rangle \tag{1}$$

where:

- $PL = \{pl_1, pl_2, \ldots, pl_n\}$ denotes a finite set of n players $pl_1, pl_2, \ldots, pl_n$, such that $n > 1$ and $n\epsilon\mathbb{N}$.
- $S = \{s_1, s_2, \ldots, s_m\}$ denotes a finite set of m strategies $s_1, s_2, \ldots, s_m$.
- U is a utility function which we express as data transmitted D_i (in bytes) per energy used E_i (in joules). Symbolically, $U = f(D_i, E_i) = D_i/E_i$ for all players PL, i.e., $U = \{u_1, u_2, \ldots, u_n\}$, denotes the set of utility values of all the players PL. The variables D_i and E_i respectively represent data transfer and energy used by a player i.
- Γ represents the decision timings: $(t_1, t_2, \ldots, t_k)$ at which players PL execute their strategy choice s_k.

Our aim is to provide a solution to the game by finding strategic set $S^* = (s_1^*, s_2^*, \ldots, s_n^*)$, that will maximize the utility for each node. We assume that each node is rational and desires to maximize its utility. Since we express utility for each node as D_i/E_i, where D_i and E_i represents the data transmitted by the node and the corresponding energy used in achieving the transmission, our solution is a strategic set S^* that:

$$\begin{aligned} &\underset{i=1,\ldots,n}{\text{maximize}} && \frac{D_i}{E_i} \\ &\text{subject to} && E_i > 0 \end{aligned} \tag{2}$$

For every player k and the rest of the players denoted as $\bar{k}$, the revenue or utility received u_k, is a function of the strategy s_k selected by the player k and strategy $s_{\bar{k}}$ of the rest of the players. Thus, the players make decisions individually, but are influenced by other players' decisions, and the outcome of the game for each player k, depends not just on its strategy s_k, but on the combined strategies $(s_k, s_{\bar{k}})$ of the player k and the rest of the players represented as $\bar{k}$. The mechanism of the game in terms of CSMA and energy used is discussed in the next section.

III. GAME FORMULATION

A. *CSMA Channel Access Probability*

The channel access probability p_a is defined as the probability of a node pl_i accessing the channel by sending its packets. The lower the contention window w_i, the higher the channel access probability p_a. In order words, for a node to have a high access probability, it needs to make use of a low contention window size. However, such access does not guarantee successful data transmission since the data packet could be lost in transit due to collisions.

Theorem 1: Let node i denote a node in an IEEE 802.15.4 network. Let p_a and w_i denote its channel access probability and its contention window, CW, receptively. Then

$$p_a = \frac{1}{w_i + 1} \tag{3}$$

where $w_i \epsilon \mathbb{Z}^+, 0 <= p_a <= 1$.

Proof: For IEEE 802.11 standard, the channel access probability expression, $p_a = 2/(w_i + 1)$ represents the state of art

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definition of p_a as used in [46], [47] and other similar works. Using this state of art expression, when $w = 0$, the expression yields $p_a = 2$ which is an absurd value for probability since $0 \leq p_a \leq 1$. This implies that the expression $w_i >= 1$ where $w_i \epsilon \mathbb{Z}^+$ must be true for all transmission in IEEE 802.11 standard. While this is compatible with IEEE 802.11 standard, the IEEE 802.15.4 standard on the other hand specifies that w_i should count down from 2 to 0 before a node could transmit.

This implies that a node could set $w = 0$ instead of $w = 2$ for instantaneous access. Therefore, the access probability for IEEE 802.15.4 standard is defined as $p_a = 1/(w_i + 1)$ and validated as follows. When $w = 0$, $p_a = 1$ for instantaneous channel access, when $w = 1$, $p_a = 0.5$, when $w = 2$, $p_a = 0.33$ and when $w = 3$, $p_a = 0.25$ and so and so forth. This definition enables us to avoid the absurd result: $p_a = 2$ for probability. In addition, the equation in (3) represents a progressive decrease in p_a as w increases which is the expected trend. Q.E.D.

To the best of our knowledge, this is the first proposed expression for channel access probability in IEEE 802.15.4 standard.

From (3), the probability of non-access $p_{\bar{a}} = 1 - p_a$, i.e., complementary probabilities, therefore,

$$p_{\bar{a}} = \frac{w_i}{w_i + 1} \tag{4}$$

B. CSMA Data Transmission Probability

The success probability p refers to the probability of successful data transmission which is different from the channel access probability p_a discussed above.

Theorem 2: Let p denotes the probability of successful transmission of a packet by a node in an IEEE 802.15.4 network. Let n denotes the total number of nodes and let w denote their uniform contention window, then

$$p = \frac{w^{n-1}}{(w + 1)^n} \tag{5}$$

where $n, w \epsilon \mathbb{N}$ and $n > 1, w >= 0$.

Proof: The probability of successful transmission can be derived by considering the probability that a specific node i accessed the channel while the rest of the nodes did not, since that is the only way a node can be successful in a shared channel. This probability can be expressed as the combined probabilities that a node accessed the channel and the rest $n - 1$ nodes represented as $\bar{i}$ failed to do so. Therefore, the probability that a node i succeeds is given by:

$$p = p_a * \prod_{i=1}^{n-1} p_{\bar{a}} \tag{6}$$

where p_a and $p_{\bar{a}}$ are defined in Theorem 1 and expressed in (3) and (4) respectively.

Remark: The default implementation of IEEE 802.15.4 requires all nodes to use the same w, so we assume this is the case, which implies that w_i = w for all nodes. The preliminary simulation results in **section 5B** show that using uniform CW produce better performance than non-uniform CW and this inform our choice of uniforms CW over non-uniform CW.

By substituting (3) and (4) into (6), it follows that:

$$p = \frac{1}{(w + 1)} * \prod_{i=1}^{n-1} \frac{w}{(w + 1)} \tag{7}$$

$$=> p = \frac{w^{n-1}}{(w + 1)^n}$$

which is equivalent to (5) and $n > 1$, since a minimum of 2 players are required for a CSMA contention game, $w >= 0$, $n, w \epsilon \mathbb{Z}^+$ and the contention window w must be a non-negative integer. $Q.E.D.$

To the best of our knowledge, this is the first proposed expression for data transmission probability in IEEE 802.15.4 standard.

In Table II, we show the values of p_a and p when the number of nodes n is fixed at 5 and the contention window, w, changes from 0 to 15. The graphs in Fig. 3a and Fig. 3b were plotted using Table II which we populated using equations (3) and (5) for $n = 5$ nodes. The graphs show the visualisation of the probability of channel access, p_a, and the probability of successful data transmission, p, respectively against the contention window CW (w), for a node i. The Fig. 3a shows that as the CW increases from 0 to 15, the access probability decreases until it attains the lowest and stable condition. Conversely, as shown in the graph in Fig. 3b, the probability of successful data transmission increases as the CW increases until it peaks at an optimal point and then declines. As proven later in Theorem 4, section 4, this shows that there is an optimal value for the contention window, CW, given any number of nodes.

w	p_a	p (for n=5)
0	1.0000	0.0000
1	0.5000	0.0313
2	0.3333	0.0658
3	0.2500	0.0791
4	0.2000	0.0819
5	0.1667	0.0804
6	0.1428	0.0771
7	0.1250	0.0733
8	0.1111	0.0694
9	0.1000	0.0656
10	0.0909	0.0621
11	0.0833	0.0588
12	0.0769	0.0558
13	0.0714	0.0531
14	0.0667	0.0506
15	0.0625	0.0482

TABLE II: Access Probability, p_a and Success Probability p for n = 5 nodes

Remark: We derived (5) as a general equation for the probability of successful transmission in IEEE 802.15.4 shared channel, with n number of nodes using the same CW, w. This equation implies that the probability of successful data

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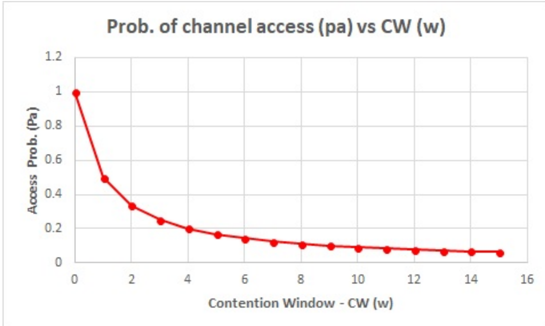
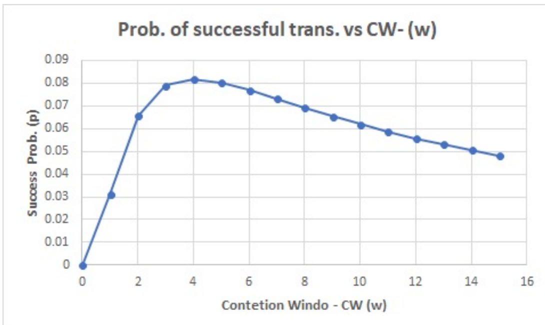


(a) CSMA Channel Access Prob. vs CW



(b) CSMA Data Trans. Prob. vs CW

Fig. 3: Channel Access and Data Transmission Prob.

transmission in IEEE 802.15.4 is a function of 2 variables: the number of nodes competing for the channel and the CW being used by the nodes. However, these nodes (players), do not have control over the number of other nodes they will be sharing the channel with at any point in time. The only variable in their control is their CW. This is the reason for choosing this variable, together with the nodes' energy as strategic variables for optimisation in our game as explained section 4. To the best of our knowledge, the derived mathematical expressions from (3) to (7) above have not been used anywhere in relation to IEEE 802.15.4 and IoT, they are unique to our study as shown in the above derivations.

C. Energy Consumption

According to [48] and [49], the energy used by IEEE 802.15.4 node can be calculated by considering the various communication phases required in transmitting and receiving data. When a node has a packet to transmit, it first senses the channel and then performs the first CCA (CCA1) and then the second CCA (CCA2), before transmitting its frame. In our derivation of energy used, we use the following notations:

Parameters Symbols	Descriptions
E_u	total energy used
E_a	available energy
E_{pkt}	energy used for payload
E_{ack}	energy used for ACK
E_{pack}	energy used for Payload and ACK
E_{csma}	energy used for CSMA contention
E_s	the energy used for sensing the Channel
E_{bf}	energy used for Back-off
E_{cca}	energy used for CCA1 and CCA2

TABLE III: Nomenclature Table-B

The E_{csma} can be expressed as:

$$E_{csma} = E_s + E_{cca} + E_{bf} \tag{8}$$

The E_{csma} includes the energy used in all channel access attempt up to and inclusive of the first successful channel access. The total energy (in joules) used in transmission, E_u, is the sum of the energy used to transmit the payload, E_{pkt}, the energy used in receiving Acknowledgements (ACK), E_{ack}, and the energy used in CSMA overhead, E_{csma}. Let X denote a random variable for the number of independent trials (i.e. channel access attempts) until and inclusive of the first successful attempt, then X is a geometrical distribution (by definition) and we can express the total energy used, E_u as follows:

$$E_u = E_{pkt} + E_{ack} + \mathbb{E}(X)E_{csma} \tag{9}$$

Where $\mathbb{E}(X)$ denotes the expectation for the random variable X.

X_k	$x_1 = 1$	$x_2 = 2$	$x_3 = 3$	...
$P(X = k)$	p	$(1-p)p$	$(1-p)^2p$	...

TABLE IV: Probability values of a random variable X

Theorem 3: Let p denote the probability for the first successful attempt for the random variable X. Then $\lim_{N\to\infty} \mathbb{E}(X) = p^{-1}$.

Proof: The probability distribution of a random variable X supported on positive natural numbers, $\mathbb{N}^+$, is a geometric distribution whose values could be $X = 1, 2, 3, ...N$. Then $X > 0$ since we cannot have zero trial resulting in a successful attempt, i.e. at least one trial is needed for a successful outcome and the trial process stops at the first successful outcome, N. The Table IV shows the Probability values of the random variable (X). In this scenario, the probability $P(X = k) = p(1-p)^{k-1}$ from Table IV, thus the expected value $\mathbb{E}(X)$ of the random variable X can be derived as follows.

$$\mathbb{E}(X) = \sum_{k=1}^{N} kp(1-p)^{k-1} = p\sum_{k=1}^{N} k(1-p)^{k-1} \tag{10}$$

which can be rewritten as follows.

$$\mathbb{E}(X) = p\sum_{k=1}^{\infty} k(1-p)^{k-1} - p\sum_{k=N+1}^{\infty} k(1-p)^{k-1} \tag{11}$$

$$\mathbb{E}(X) = p\sum_{k=1}^{\infty} k(1-p)^{k-1} - \delta(p) \tag{12}$$

where $\delta(p) = p\sum_{k=N+1}^{\infty} k(1-p)^{k-1}$ is a trivial value.

Using derivative rule, (12) can be rewritten as:

$$\mathbb{E}(X) = p(-\frac{d}{dp}\sum_{k=1}^{\infty}(1-p)^k) - \delta(p) \tag{13}$$

Using the sum of infinite series in the above equation, we have:

$$S_\infty = \sum_{k=1}^{\infty}(1-p)^k = \frac{1-p}{p} \tag{14}$$

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We substitute this in (13) as follows:

$$\mathbb{E}(X) = p(-\frac{d}{dp}(\frac{1-p}{p})) - \delta(p) \tag{15}$$

$$\mathbb{E}(X) = p(\frac{d}{dp}(1-\frac{1}{p})) - \delta(p) = \frac{1}{p} - \delta(p) \tag{16}$$

Since the probability of success $p < 1$, $0 < 1-p < 1$ and $(1-p)^{k-1}$ is a small value, the expression $\delta(p) = p\sum_{k=N+1}^{\infty} k(1-p)^{k-1}$ will be trivial accordingly, hence $\delta(p)$ approaches zero as $N \to \infty$. Therefore,

$$\lim_{N\to\infty} \mathbb{E}(X) = p^{-1} \tag{17}$$

as stated in Theorem 3 above. Q.E.D.

Using the above derivation of $\mathbb{E}(X)$ in (9), we have:

$$E_u = E_{pkt} + E_{ack} + p^{-1}E_{csma} \tag{18}$$

For convenience, we merge the energy used in transmitting the payload, E_{pkt} and energy used in receiving the ACK, E_{ack} into one as follows:

$$E_{pkt} + E_{ack} = E_{pack} \tag{19}$$

and substitute this in (18) to obtain:

$$E_u = E_{pack} + p^{-1}E_{csma} \tag{20}$$

IV. GAME UTILITY

A. Utility Function

The utility value of a player refers to a player's satisfaction associated with the chosen strategy and is derived from the pay-off or revenue function. In our game formulation, we express the utility function as the amount of data transmitted by a node i per unit of energy used. This translates to the strategy of making the best use of the available energy E_a to derive the maximum value for utility expression $U_i = D_t/E_u$ where D_t denotes the data transmitted and E_u denotes the energy used to transmit the data.

This is based on the rationality assumption that all nodes are forward looking, hence they want to get the highest data transmission from their available energy E_a. Thus, the selection of their CW w will be dependent on the maximization of their utility function subject to their available energy. The ratio D_t/E_u is based on probability of successful data transmission, therefore, from our game definition in (1), the utility of a node can be expressed as:

$$U_i = \frac{D_t}{E_u} \tag{21}$$

Therefore, using (20) in the above, we have:

$$U_i = \frac{D_t}{E_{pack} + p^{-1}E_{csma}} \tag{22}$$

and by substituting the value of p from (5) into (22) we have:

$$U_i = \frac{D_t}{E_{pack} + w^{n-1}(1+w)^{-n}E_{csma}} \tag{23}$$

The experimental values of power drawn with times for the various phases of communication are as shown in Table V,

$Phase$	$Power(mW)$	$Time(ms)$
Initialization - wakeup	44	4.000
Contention - CSMA	72	2.000
Transmit - TX (1Byte)	90	0.032
Receive - RX (1Byte)	72	0.032
TX-RX Switching	54	0.400
Acknowledgement - ACK	72	1.400

TABLE V: Transmission Phase and the Power Consumed

Symbols	Meaning	Values
D_t	Packet Size	$127Bytes$
E_p	Energy used for payload	$365.76\mu J$
E_{ack}	Energy used for ACK	$100.80\mu J$
E_{pack}	E_p + E_{ack}	$466.56\mu J$
E_{csma}	Energy used for CSMA	$144.00\mu J$

TABLE VI: Table of Constants

using [48] and [49]. We can therefore calculate the expected value of energy used for transmitting a packet as shown in Table VI.

The total energy used in transmission, E_u is the sum of the energy used to transmit the payload, E_p, energy used in waiting for ACK, E_{ack} and the energy used in CSMA overhead represented as E_{csma}, but the E_{csma} can be expressed as $E_{csma} = E_s + E_{cca} + E_{bf}(J)$ where E_s = Energy used in sensing the channel, E_{cca} = Energy used for CCA1 and CCA2 while E_{bf} = Energy used during back-off period.

We convert the values of power to Watts and time to seconds in Table V and estimate the energy used in Joules (J) for each transmission phase as follows:

$$E_{pkt} = 90*10^{-3}*32*10^{-6}*127 = 365.76*10^{-6}(J) \tag{24}$$

where a standard IEEE 802.15.4 packet is 127 bytes in size.

$$E_{ack} = 72*10^{-3}*1.4*10^{-3} = 100.80*10^{-6}(J) \tag{25}$$

$$E_{pack} = 365.76*10^{-6} + 100.80*10^{-6} = 466.56*10^{-6}(J) \tag{26}$$

$$E_{csma} = 72*10^{-3}*2.0*10^{-3} = 144.00*10^{-6}(J) \tag{27}$$

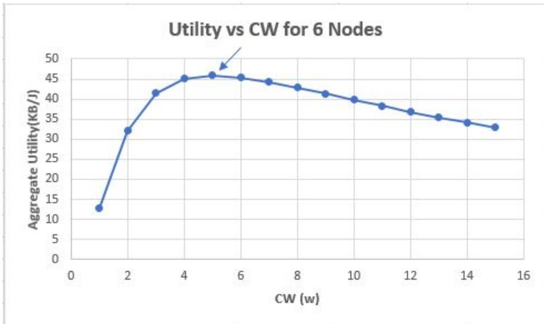
Substituting (26), (27) and $D_t = 127$ bytes into (23), we have:

$$U_i = \frac{127}{466.56*10^{-6} + 144.00*10^{-6}w^{n-1}(1+w)^{-n}} \tag{28}$$

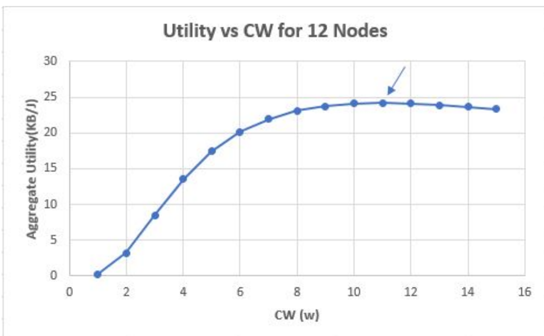
For a packet of data, the energy used in transmitting the payload and receiving the ACK, E_{pack} and the energy used for a CSMA E_{csma} are relatively constant according to [48] and [49]. The variable in (22), (23) and (28) is: $p^{-1} = w^{n-1}(1+w)^{-n}$. Therefore, we visualise the utility expression in (28) for 6 and 12 nodes by plotting the graph of utility against CW as shown in Fig. 4a and Fig. 4b. The two curves show a steady increase in the aggregate utility for nodes which is highest when all the playing nodes set the value of their CW parameter to $n-1$, i.e. $w = n-1$ as marked with arrow on each curve. The expression $w = n-1$, for optimal value of CW is proved in the next section.

B. Utility Convergence

The convergence position for the game is a stable state in which no player can choose a better strategy given that the strategies of other players remain unchanged. This will imply



(a) Utility with CW (w) for 6 nodes



(b) Utility with CW (w) for 12 nodes

Fig. 4: Equilibrium Utilities

that no player p^k will be able to increase its utility value u^k by unilaterally changing its strategy s^k. The existence of this Nash Equilibrium (NE) position for the game is evaluated as follows by optimizing the utility function U_i, in (28) with respect to w.

Theorem 4: Let p denotes the probability of successful transmission of a packet by a node i in an IEEE 802.15.4 network with all nodes using the same contention window CW, w, then the optimum CW, w for the players is given by $w = n - 1$ where n signifies the number of players or nodes and $n > 1$, $n \epsilon \mathbb{Z}^+$.

Proof: This theorem implies that, the convergent point for the game will be $w = n-1$. In other words, the NE position will be achieved when all n nodes set their CW, $w = n - 1$. In order to prove this theorem, we reconsider equation (23) as follows:

$$U_i = \frac{D_t}{E_{pack} + w^{n-1}(1+w)^{-n}E_{csma}} \quad (29)$$

For convergence points, we need to find the derivative of U with respect to w, i.e. $U^{'} = dU/dw$ and set the result to zero as follows:

$$U^{'} = 0 - (D_t E_{csma}((1-n)w^{-n}(1+w)^n + nw^{1-n} (1+w)^{n-1}))/(D_t E_{pack} + w^{n-1}(1+w)^{-n}E_{csma})^2 \quad (30)$$

$$= -D_t E_{csma}((1-n)w^{-n}(1+w)^n + nw^{1-n} (1+w)^{n-1})/(D_t E_{pack} + w^{n-1}(1+w)^{-n}E_{csma})^2 \quad (31)$$

We set $U^{'} = 0$ as follows to determine the critical points.

$$= \frac{-w^{-n}(1+w)^n D_t E_{csma}((1-n) + nw(1+w)^{-1})}{(D_t E_{pack} + w^{n-1}(1+w)^{-n}E_{csma})^2} = 0 \quad (32)$$

$$= \frac{-w^{-n}(1+w)^n D_t E_{csma}((1-n) + nw(1+w)^{-1})}{(D_t E_{pack} + w^{n-1}(1+w)^{-n}E_{csma})^2} = 0 \quad (33)$$

$$=> -w^{-n}(1+w)^n D_t E_{csma} = 0, \quad or \frac{(1-n)}{1} + \frac{(nw)}{(1+w)} = 0 \quad (34)$$

$$=> w = 0, \quad or \quad \frac{(1-n)(1+w) + nw}{(1+w)} = 0 \quad (35)$$

$$=> w = 0, \quad or \quad \frac{(1 + w - n - nw + nw}{1+w} = 0 \quad (36)$$

$$=> w = 0, \quad or \quad 1 + w - n - nw + nw = 0 \quad (37)$$

$$=> w = 0, \quad or \quad w = n - 1 \quad (38)$$

as stated in theorem 4 above, Q.E.D.

The above derived expression $w = n - 1$ shows that the all players get the best value for their utility when they set the contention window to the value $n - 1$ where n refers to the number of nodes. This point at which all nodes receive the best value for their utility is also refer to as Pareto optimal for the game. Therefore, in an ideal situation all players would work towards this equilibrium position. However, due to the circumstance of individual player such as load level or available energy or selfish motive, they may be motivated to deviate from the action or strategy that is best for all, therefore we considered other various possible scenarios in the next subsection.

C. Utility Strategies

1) Optimal CW Size: The expression in (38) shows two convergent points of $w = 0, n - 1$, which means that an equilibrium can be achieve in either case, however setting the $w = 0$, will lead to multiple collisions and consequently energy loss. It will also result in lowest utility which is observable on the utility graphs in Fig. 4a and Fig. 4b, hence we considered $w = 0$ as a minimal position. However, setting $w = n - 1$ provides the greatest utility as shown by the peak positions on the curves.

No of Players (n)	3	4	5	6	7	8	9	10	...
Optimal CW (w=n-1)	2	3	4	5	6	7	8	9	...

TABLE VII: Optimal CW (w) for n Players

This implies that setting $w = n - 1$ will be considered more appropriate by all rational players who wish to maximize their utilities. The Table VII shows the variation of the optimal contention windows CW, $w = n-1$ with the number of nodes n. Similarly, the graphs of our utility equation in (28) indicate the corresponding peak positions for utility at the optimal contention window, $w = n - 1$. as shown in Fig. 4.

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2) Flexible CW Size Based on Load: We model the process of packet transmission as a cost-benefit analysis game by formulating our utility function as the ratio of data transmitted to the energy used, so that nodes could optimise the two objectives at the same time. However, since the level of loads and the available energy may vary from node to node, the desire to transmit data or to save energy will also vary from node to node. We model this flexibility requirement with the use of Table VIII as follows.

Load Level	CW (w) Range
High	$<< n-1$
Medium High	$< n-1$
Normal	$= n-1$
Low	$> n-1$
Very Low	$>> n-1$

TABLE VIII: Load Level and CW Sizes

In Table VIII, despite the fact that the optimal value for CW is $w = n - 1$ as derived in (38), a node that has high load level may be motivated to deviate from this rule by setting its w to a value less than $n - 1$ to gain more throughput at the expense of its energy, provided it has available energy to do so. Similarly, a node that has less load could set its CW to a value more than $n - 1$ to save more energy.

E_a *Level*	CW (w) Range
High	$<< n-1$
Medium High	$< n-1$
Normal	$= n-1$
Low	$> n-1$
Critical	$>> n-1$

TABLE IX: Energy Level and CW Sizes

3) Flexible CW Size based on Available Energy: In a similar manner to the above flexibility, the Table IX shows the flexibility of our CW with available energy E_a. Although the optimal value for CW is given as $w = n - 1$, a node with higher available energy E_a may be motivated enough to set a lower value for its CW to transmit more data at the expense of its energy. Conversely, a node whose available energy E_a has reached the critical state could be motivated to set its CW to a value higher than $n - 1$ to save energy and achieve longevity. As far we know, this degree of flexibility of CW is unique to work.

D. Summary of the Game

One of the objectives of our game is to add flexibility to the CSMA algorithm which is not available in the current version. In the current CSMA version of IEEE802.15.4, the CW is set to 2 by all nodes and decremented to zero for a node to transmit. In our version of CSMA, we proposed a flexible value for CW. In an ideal situation or best-case scenario, all cognitive nodes are to play cooperatively by setting their CW to the optimal value $w = n - 1$ based on the number of perceived nodes n. In this scenario, all the nodes will derive the best possible utility which cannot be improved on without making at least one player worse off. Hence this signifies a Pareto optimal position which refers to a situation in which the resources in a system are distributed in the most efficient manner.

Although this Pareto optimal position provides the best resource sharing result, it is rarely achieved. This is because, individual selfish motives and circumstances in terms of load and energy level usually prevail over the need to cooperate with the rest of the players in order to achieve the best possible outcome for all. This is synonymous to the Prison dilemma and Stag hunt game in which individual selfish interest prevails over the corporate interest leading to corporate loss. Therefore, in addition to the Pareto efficiency scenario which is our proposed default mode for cognitive node, we also considered a situation in which individual nodes act on their own by setting their CW strategy based on their needs and motivations.

V. SIMULATION AND EVALUATION

A. Experimental Setup

In the experimental setup, a typical example of a home WPAN is considered. This consist of various home devices like TV, Internet radio or stereo system, mobile phone, IPAD, laptop or desktop, home automation device, energy metre, and any other Wi-Fi enable device acting as nodes or players. In such a scenario, the router or access point acts as the PANC, while the other 10 nodes form a star topology round the PANC as shown in Fig. 5. These 10 nodes are divided into two groups. The two groups were made to play 2 different variants of the protocol so that the we can compare their output.

The simulation is based on the MATLAB-based Probabilistic Wireless Network Simulator (Prowler) [50]. In the simulation, the physical layer data rate of 250kbps at 2.4 GHz was used and all packets are set at same default length and size. The contention period was set to 1000 slots and the backoff stage was fixed at macMinBE. Although the default CW = 2 was set initially for all nodes, each node has the flexibility of changing their CW in accordance with their strategies. The other simulation parameters are set as shown in the Table X below.

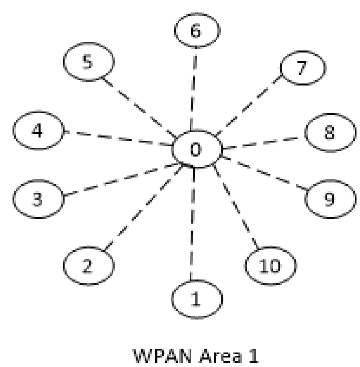

Fig. 5: IEEE 802.15.4 WPAN Setup

B. Preliminary Investigation

A lot of research has been carried out in the use of both uniform and non-uniform CW in the CSMA contention in wireless network. While some authors suggest that variable CW leads to better performance as in the works in [51], [52], others works such as [53], [54] suggest the opposite is true

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Simulation Parameters	
Simulation Parameters	Values
BE_{min}	3
BE_{max}	8
Packet Length	1 slot
1 slot	20 symbol
Channel frequency	2.4 GHz
Radio Type	IEEE 802.15.4 radio
Channel frequency	2.4 GHz
MAC Layer	802.15.4 MAC
Normal Mode	1 PANC and 10 motes
Packet-size	127 bytes
Simulation Time	24000 sec (400 cycles)
$Transmit_{power}$	90mW
$Receive_{power}$	72mW
ACK_{power}	24mW
$Sleep_{power}$	1mW
$Wakeup_{power}$	44mW
CCA_{power}	72mW
Initial Energy E_a	1J, 50J

TABLE X: Simulation Parameters

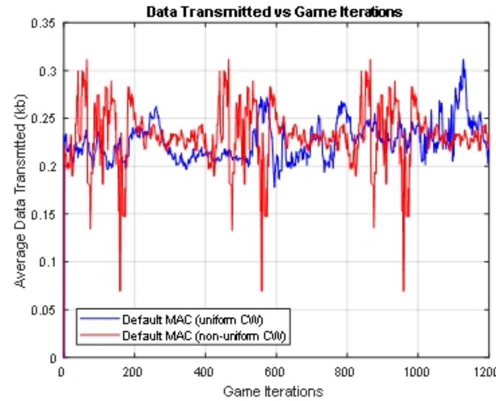
by proposing a fixed or uniform CW. We view this apparent variation in research result from 2 perspectives: The first perspective is the fact that different works use different metrics to measure performance: some use data throughput only while others include the cost of such throughput. In addition to this difference in measuring criteria, the CSMA algorithm uses CW differently in IEEE 802.11 and IEEE 802.15.4 standard and this difference could skew experimental results for different standards. Therefore, in order to validate our model, we first investigated 2 models of the default IEEE 802.15.4 protocol: one using uniform CW and the other using non-uniform CW. The output data are evaluated for both simulation as shown in Fig.6.

Remark: The data transmitted is higher for nodes using non-uniform CW as shown in Fig. 6a, however when the cost of energy is added to the equation, the uniform CW performs better as shown in Fig. 6b. This informs our preference for uniform CW in our game formulation in **section 3B** and subsequent simulation runs.

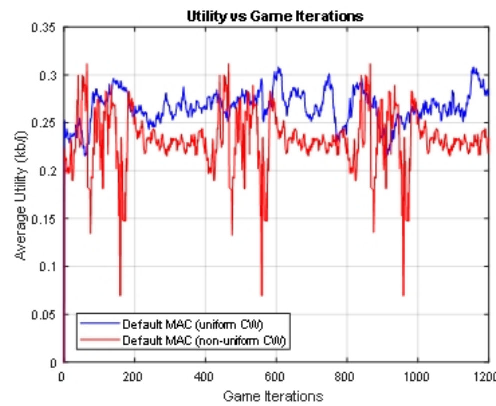
C. Smart MAC Simulation

Using the above experimental set-up, we simulated a non-cooperative home WPAN environment with 10 nodes in addition to the PANC. The same number of packets load (1000 packets) were assigned to each node so that they always have packet to transmit and 10 Joules of energy were assigned to each node. However, 5 nodes were made to play the IEEE 802.15.4 in its default mode (i.e CW = 2) while the remaining 5 were made to play our smart game model with ability to cooperate with one another by setting the setting optimal CW and the ability to act individually in a non-cooperative mode by modifying their CW w subject to their individual's strategy.

The simulation was repeatedly run for 1200 iterations and the combined utilities D_t/E_u, energy used E_u, and available energy E_a during simulation were written into a file for the 2 classes of nodes: smart MAC and the default MAC. The 2 files were then analysed and visualised graphically. The resulting graphs are as shown in Fig. 7 and Fig. 8 which, as discussed below, suggest a higher performance for our model in terms of utility, energy savings and longevity when



(a) Default MAC Data Transmitted



(b) Default MAC Utility

Fig. 6: Default MAC: Uniform Vs Non-uniform CW

compared with the default implementation.

D. Evaluation of Utilities

We considered the 2 scenarios of cognitive behaviour: co-operative smart MAC and non-cooperative smart MAC. These 2 scenarios were compared with the default implementation of IEEE 802.15.4 in terms of utility. The cooperative smart behaviours denotes a scenario in which all our smart nodes cooperate with one another and set their CW to the optimal value $w = n - 1$, in order to achieve optimal utilities and fairness for all players, while the non-cooperative smart MAC behaviour denotes a scenario in which each of our cognitive nodes plays a selfish strategy by setting their CW individually, based on their motivations and chosen strategies thereby disregarding our rule of setting optimal CW for the benefit of all nodes. The graphs of the utility for both scenarios are as shown in Fig. 7. As expected, the result shows that higher utility is achieved against the default standard IEEE 802.15.4 MAC when all the smart nodes cooperate by setting their CW to the optimal value, $w = n - 1$ as shown in Fig. 7a in comparison with Fig. 7b in which the nodes play their individual selfish strategies rather than cooperating.

E. Evaluation of Energy Used

The graphs of energy used and available energy with game iterations for the 2 categories of nodes: smart MAC and default

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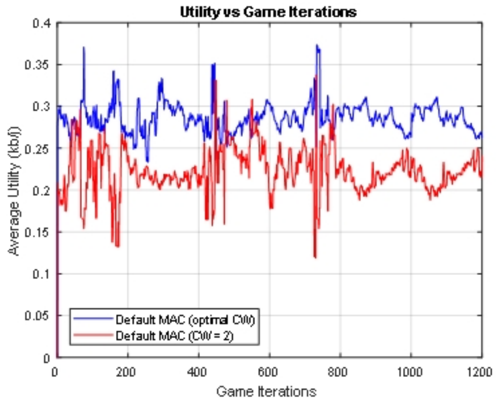
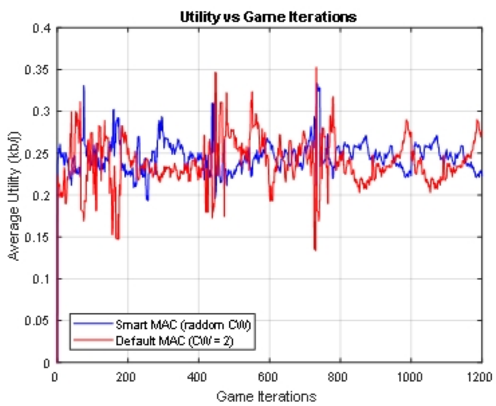


(a) Smart MAC (optimal CW) Utility Graph (1-1200 rounds)



(b) Smart MAC (random CW) Utility Graph (1-1200 rounds)

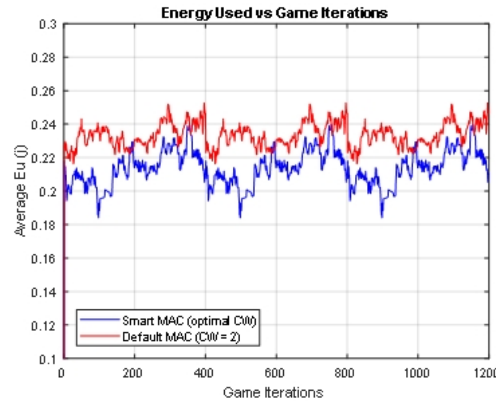
Fig. 7: Graphs of Utility

MAC are as shown in Fig. 8. We allocated 10 joules of energy to each node resulting in 50 joules of energy for our smart nodes and 50 joules of energy for the default IEEE 802.15.4 Standard as initial energy for the 2 classes of nodes at the onset of our simulation.

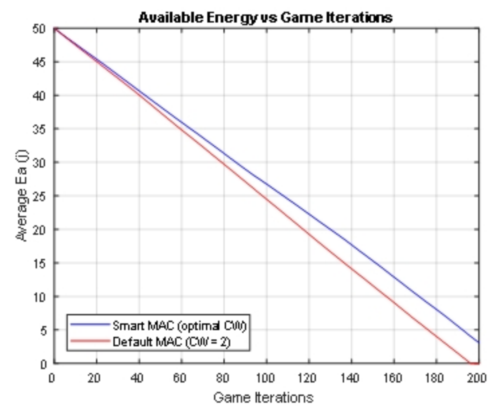
We ran the simulation game repeatedly until the nodes' energy runs out. The results show that for the same level of playing conditions such as number of competing nodes, load level and initial energy assigned to the 2 classes of node, the average energy used by smart nodes, which is represented in blue colour, is consistently lower than the aggregate energy used by the default IEEE 802.15.4 which is represented in red colour in the Fig. 8a.

F. Evaluation of Available Energy

Similarly, the graph in Fig. 8b shows the variation of available energy with game iterations for the 2 categories of nodes. In evaluating the available energy for each group of players, we repeated the experiment with the same 50 joules of energy allocated to each node as their initial energy as in the previous simulation run. The simulations were run repeated as before until the nodes' energy runs out and the resulting graphs shows that, the average available energy for the smart nodes which is represented in blue colour, is consistently higher than the average available energy for the default IEEE 802.15.4 standard which represented in red colour.



(a) Energy Used for 1-1200 rounds of game cycle



(b) Available Energy for 0-200 rounds of game cycle

Fig. 8: Graphs of Energy Used and Available Energy

G. Explanation of Utility and Energy Graphs

The above simulations were repeatedly run for 1200 iterations and the output graphs shows that, for the fixed playing conditions such as number of competing nodes, load levels of these nodes and initial energy assigned to them, the average utilities for our model, represented in blue colour in Fig. 7 is consistently higher than the average utilities of the default IEEE 802.15.4 represented in red colour. In the smart and cooperative mode, all of our nodes cooperate by setting their CW to the optimal values and get high combine utility when compare with the default IEEE 802.15.4. In the smart but non-cooperative mode, the individual nodes set their CW as desired. The resulting graph in Fig. 7a and Fig. 7b shows that cooperative cognitive achieve higher utility against the default IEEE 802.15.4 than the non-cooperative cognitive nodes as expected.

In addition, the result suggests that for both smart cooperative mode and smart non-cooperative mode scenarios, the combined utilities (data transmitted per energy used) for the model is consistently higher than the combined utilities for the default implementation of IEEE 802.15.4 in all the simulation graphs. The only factor we could attribute to this is the effect of our smart algorithm evaluating the expected probability of

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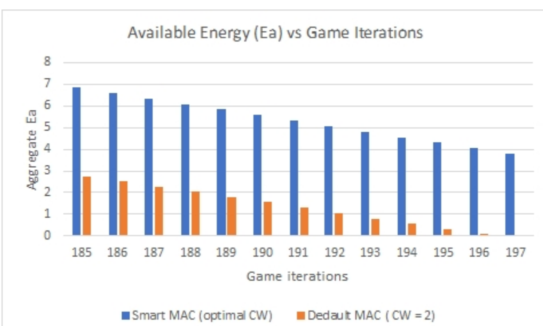
successful data transmission, the available energy and the load level of a node and making a smart decision in setting their CW w based on these values to maximise their utilities. The default implementation of IEEE 802.15.4 is not capable of such optimisation to the best of our knowledge. Similarly, the results for energy used and available energy follow a similar trend shown in Fig. 8.

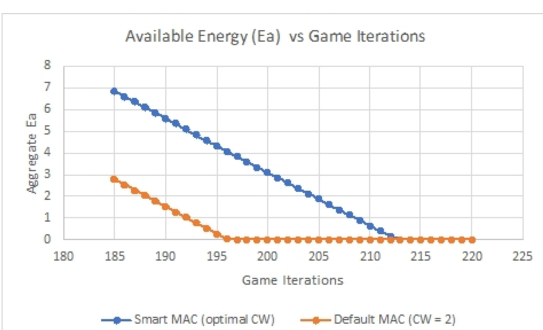
H. Evaluation of Longevity

In evaluating the longevity of nodes, we allocated 50 joules of initial energy to each group of nodes (i.e. 10 joules per node for 5 nodes) and then ran the simulation repeatedly until one group of nodes run out of their 50 joules of energy completely. The simulation graphs in Fig. 9 shows the longevity trend of our smart nodes as compared to the default implementation of IEEE 802.15.4 nodes.

The results show a progressive decline in the available energy for both smart nodes and the IEEE 802.15.4 Standard with increase in the number of game iterations. However, the rate of decline in the available energy for our smart nodes is lower than the rate of decline in available energy for the default MAC. This pattern continues throughout the simulation runs as indicated by the graphs in Fig. 9a and Fig. 9b, until the game reaches 195 - 197 game cycles as shown in Fig. 9a and Fig. 9b in which case, the available energy of the default MAC group declined to zero thereby ending the game for the default MAC nodes. As shown in Fig. 9a and Fig. 9b, the game terminates at 197 iterations because the default MAC group ran out of their available energy as shown by the reduction of their available energy to zero level in Fig. 9b. This is also indicated by the disappearance of the red bar in the 197 iteration in the Fig. 9a.



(a) Available Energy for 185-197 rounds of game cycle



(b) Available Energy for 185-220 rounds of game cycle

Fig. 9: Graphs of Longevity

In evaluating the longevity of the cognitive nodes, we continued with the simulation run after the default MAC group has ran out of their available energy so that we can extrapolate our result as shown in Fig. 9b. The smart group, too, eventually ran out of their available energy as expected, but this doesn't happen until after 212 game cycles as indicated by the intersection of the blue graph with the X-axis in the Fig. 9b. This led to our conclusion that, given the same level of playing conditions such as number of competing nodes, load level and the same initial energy assigned to the 2 groups of node, the average available energy for our smart nodes (in blue colour) is consistently higher than the average available energy of the default IEEE 802.15.4 (in red colour), hence our model has a higher potential for longevity than the standard implementation.

This result is consistent with our expectation in the sense that, in our previous simulation runs as discussed above, the energy used by the default MAC nodes is consistently higher than the energy used by the smart MAC nodes. That is, since the same amount of energy was initially assigned to both groups at the onset of the game, the default MAC group that used more energy is expected to have less energy available and vice versa.

I. Evaluation of Scalability

The simulation result presented in Fig. 11 and Fig. 12a shows the scalability test for 6 nodes using 500, 1000 and 1200 game iterations respectively. The result was obtained by keeping the number of nodes constant at 6 while changing the number of iterations to 500, 1000 and 1200 respectively. In all of the simulation runs (of which we present 500, 1000 and 1200 iterations), the result support the view that the average utility for the smart MAC model is higher than the average utility for the default MAC model regardless of the number of iterations. The graphs in the figure show that the result for 500 iterations is contained in the result for 1000 iterations and the result for 1000 iterations is contained in the result for 1200 iterations. The only difference is the run time which determines the length of the graphs. The three graphs have similar shape and pattern. This similarity in result suggests that the number of iterations has no overall effect on the game result.

Next we keep the number of game iteration constant and investigate the scalability of our model with varying number of nodes. We simulate multiple network areas with different number of nodes and the nodes in one location are not aware of the nodes in the other location which is a typical scenario expected in a WPAN. These multiple network areas are on different contention domains because they are using orthogonal frequency channels, hence there are no collisions between the transmissions from the different regions. This arrangement or scenario has a significant effect on the result of the game as shown in the simulation graphs in Fig. 12 - Fig. 13. The multiple areas are named as Area A, B, C. D with 6 nodes, 10 nodes, 12 nodes and 16 nodes respectively as shown in the Fig. 10. Area A could be synonymous with car WPAN with 6 nodes while Area B could be synonymous

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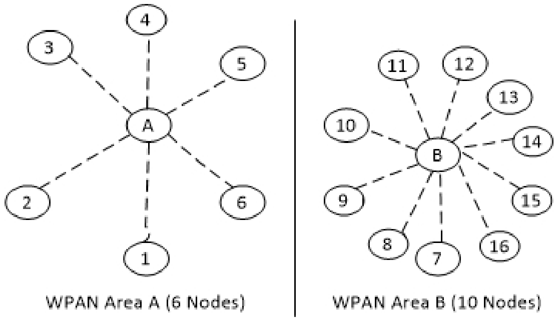
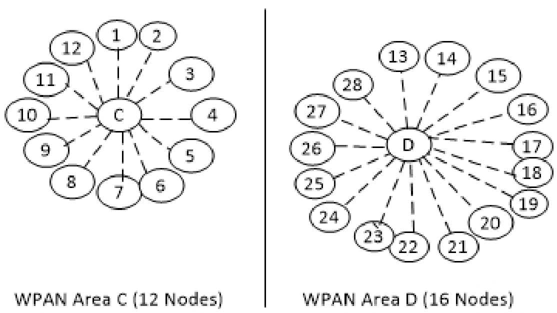


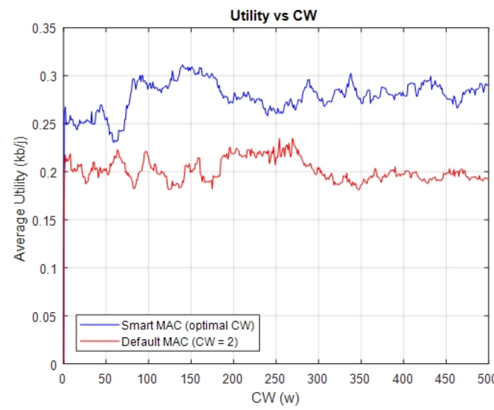
(a) IEEE 802.15.4 WPAN Setup



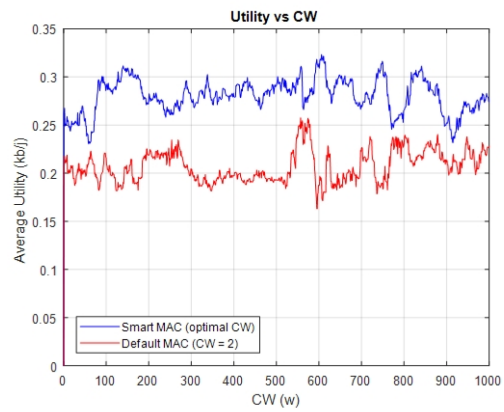
(b) IEEE 802.15.4 WPAN Setup

Fig. 10: Test of Utility in different Areas

with small home office WPAN with 10 nodes and so on. These groups of nodes use different but uniform CW based on the number of perceived nodes in their respective areas. The simulation graphs for the different areas are as shown in Fig. 12 - Fig. 13 which indicate that the utility achieved by the smart model is higher than the utility achieved by the default implementation of IEEE 802.15.4 standard in all locations. The difference in the graphs also corresponds to the difference in the number of contending nodes in all the locations. Therefore, our evaluation of scalability is based on the number of competing nodes (i.e the size of the local IoT network) rather than the number of game iterations since the number of iterations has no effect on the result of the game.



(a) Smart MAC (cooperative) Utility for 500 iterations



(b) Smart MAC (cooperative) Utility for 1000 iterations

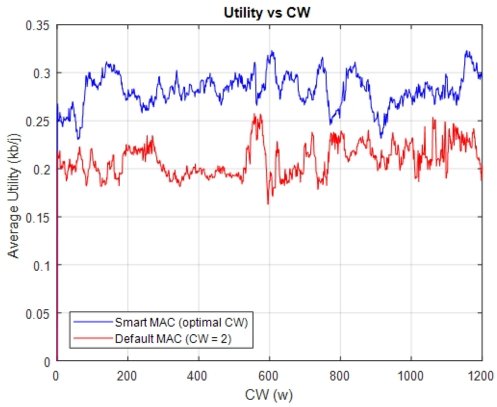
Fig. 11: Scalability Test for 6 nodes

VI. CONCLUSION

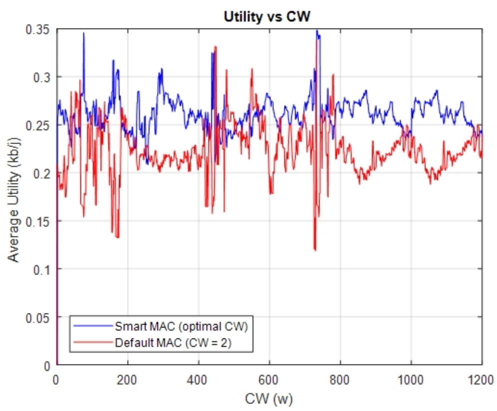
We have established that in an IoT environment using IEEE 802.15.4, each node can work out the optimal value of CW that will lead to the highest utility for all nodes and thus set their CW to this calculated value in order to achieve better performance. The mathematical analysis and simulation results show that the CW set in this manner will enable the network to perform in an optimal level which will be beneficial to all nodes by improving transmission efficiency in terms of the amount of data transmitted and the energy used in transmitting such data. That is, it will enable devices to achieve higher data transmission per unit of energy used. The significance of this finding is that there is no need to set the contention window parameter to a predefined value in the protocol as we currently have. On the contrary, it is better to make it a dynamic variable calculated and set at run time by the competing nodes.

In the smart game, a utility function that is based on data transmitted and energy used is formulated and a stable condition for the game is established in a non-cooperative environment. The simulation results suggest a higher transmission efficiency, (with regards to data transmission and energy saving), for our scheme over the current default scheme. It therefore confirms that, with some tweaking, our scheme can yield a better rate of data transmission at low cost of energy, leading to efficiency in data transmission and longevity for IEEE 802.15.4 standard and IoT devices. Therefore, our recommendation is that, in the future version of the protocol, the current principle of setting a predefined value of CW in the protocol should be replaced with our consensus principle in which all nodes calculate the optimal value of CW and dynamically set the value of their CW accordingly.

Through a combination of design mechanisms such as smart game, and the choice of utility function that uses the principle of cost-benefit analysis (CBA), we established that it is possible for nodes to maintain a favourable balance between data transmitted and energy used. This becomes significant when selfish and non-selfish nodes are combined in a network as is often the case. We argued that it is possible for energy constrained nodes to maintain connectivity with longevity even under a severe load or adversarial conditions. The proposed framework is also capable of scaling with increase in the number of nodes for different contention (network) areas as shown in the evaluation of scalability. Finally, the smart model could be seamlessly integrated into the existing standard with minor

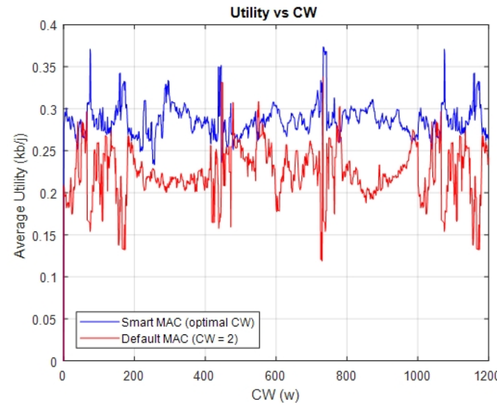


(a) Smart MAC (cooperative) Utility WPAN Area A (6 nodes)

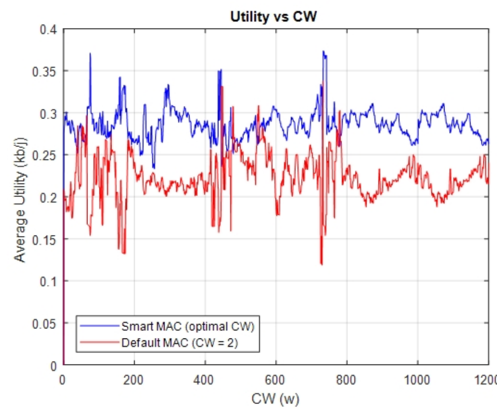


(b) Smart MAC (cooperative) Utility WPAN Area B (10 nodes)

Fig. 12: Scalability Test for 6 and 10 nodes



(a) Smart MAC (cooperative) Utility WPAN Area C (12 nodes)



(b) Smart MAC (cooperative) Utility WPAN Area D (16 nodes)

Fig. 13: Scalability Test for 12 and 16 nodes

changes. Therefore our suggestion for future work is that of tweaking and fine tuning the smart model for implementation in the next version of the IEEE 802.15.4 standard.

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