CAPCoS: Context-aware PAN Coordinator Selection for Health Monitoring of Soldiers in Battlefield

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***Abstract*—This paper presents a context-aware Personal Area Network (PAN) coordinator selection algorithm - *CAPCoS*, for real-time acquisition of physiological data of soldiers in battlefield. PAN coordinator selection procedure in Wireless Body Area Networks (WBANs), must have some WBAN specific attributes and scenario specific attributes. In this work, we consider three criteria such as – successful delivery of data packets at sink, cooperation among different hops during multi-hop routing, and health severity of individual soldiers. CAPCoS uses the concept of absorbing Markov chain in order to quantify the rate of successful delivery of packets or the Absorption Rate (AR) of each hop. The cooperation Index (CI) represents the ratio of data-out to data-in, for each hop. Priority of Health (PH) represents the normalized health severity of each soldier. In order to select the most preferable Local Processing Unit (LPU) as the PAN coordinator among all WBAN-equipped soldiers, we employ the concept of Analytical Hierarchy Processing (AHP), which generates a proper ranking of the LPUs, based on the aforementioned three criteria. We achieve around 50% improvement in both network lifetime and traffic using the proposed algorithm.**

***Index Terms*—Wireless Body Area Network, Wireless Personal Area Network, PAN Coordinator Selection, Absorbing Markov Chain, Analytic Hierarchy Processing.**

I. Introduction

Modern remote sensing technologies can be categorized broadly under Wireless Personal Area Networks (WPANs), in which remote, ubiquitous, and real-time health monitoring systems are the applications of Wireless Body Area Networks (WBANs). The procedure of PAN coordinator selection in a multi-hop network is application specific. Moreover, PAN coordinator selection in case of soldiers-health monitoring, faces challenges, such as the involvement of human health, and the minimal availability of network infrastructure in battlefields in extreme environment. The proposed CAPCoS algorithm yields substantial success while overcoming these barriers.

A. Motivation

Apart from gathering physiological information, and providing feedback notifications, soldier-health monitoring has some other important features. The soldiers' health status can directly or indirectly affect war strategies. Reliable and real-time delivery of physiological data makes it possible to analyze the sustainability of each soldier in extreme weathers, and modify war strategy accordingly. The primary barrier is the unavailability of sufficient network infrastructure in border areas, which motivates us to propose the concept of Flying Sensor Vehicles (FSVs). An FSV tracks the PAN coordinator of a soldier-cluster, collects physiological data from it, and performs necessary computations to select the next PAN coordinator of the cluster. Finally, it broadcasts the identity of the next PAN coordinator to the cluster members and to the immediate next FSV. We employ the concept of Analytical Hierarchy Processing (AHP), which considers both network and health specific metrics while selecting the PAN coordinator of a soldier-cluster. All necessary computations of the proposed algorithm, CAPCoS, are executed by the FSVs that periodically fly and monitor the whole process.

B. Contribution

The specific *contributions* of this work are as follows:

- We quantify the successful packet delivery rate of each hop with respect to the destination node in the network.
- To minimize starvation, the proposed algorithm always avoids the current coordinator during the selection procedure of the next PAN coordinator.
- The proposed concept of FSVs, that sense environmental parameters, leads to a comparative analysis of each soldier's sustainability in extreme weather.

II. Related Works

Despite significant technical advancements in remote sensing applications, especially related to ubiquitous health monitoring, and elderly patient monitoring [1]–[3] in post-modern world, the lack of sufficient literature regarding real-time health monitoring of soldiers in battlefields, is prominent. In addition, such extreme geographic locations suffer from minimal network infrastructure. Cho et al. [4] proposed a system, which consists peer-to-peer network of soldiers and WiMax-enabled unmanned aerial vehicles. Lim et al. [5] proposed a blast source localization application based on real-time health monitoring of soldiers through physiological and biomedical sensors. However, these studies lack the necessity of selecting PAN coordinator in the network.

There exist some studies on the selection of cluster head in wireless sensor networks, mainly based on LEACH [6]. Thein et al. [7] proposed an algorithm to distribute energy load among all the nodes in a cluster, during cluster-head selection, in an energy-efficient way. This extended version of LEACH tracks the remaining energy of the nodes and modifies the probability of each node to become a cluster-head. Yang et al. [8] proposed an extension of LEACH architecture with

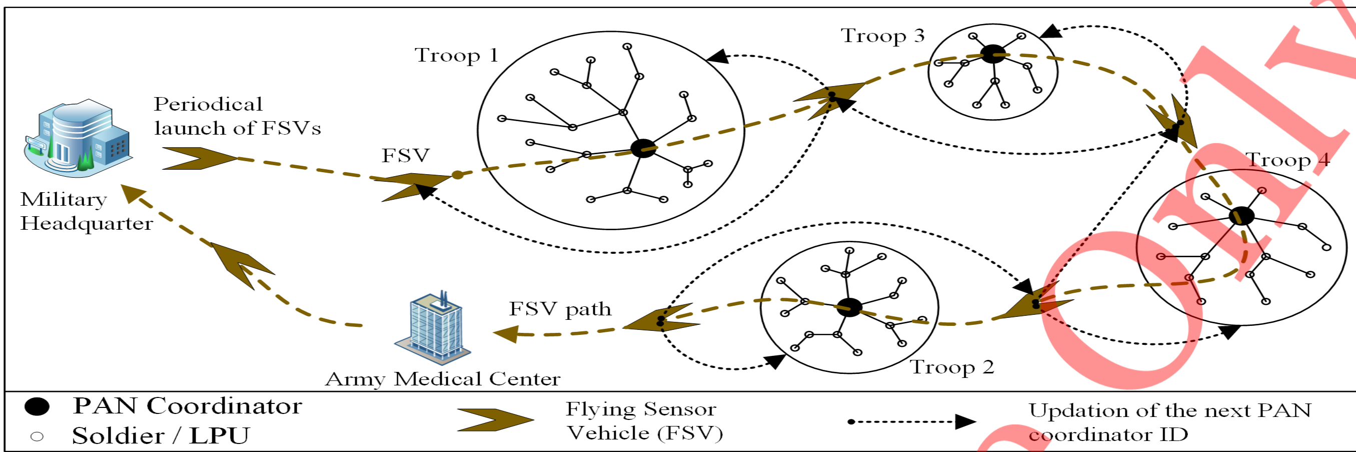

Fig. 1: Path of Flying Sensor Vehicle

sleep-wakeup based decentralized MAC protocol to minimize energy consumption. It also avoids strict requirements for synchronization in case of Time Division Multiple Access (TDMA). Junping et al. [9] proposed a time-based cluster-head selection algorithm, which is again a variant of LEACH. Handy et al. [10] extended LEACH's stochastic nature by a deterministic component in order to increase network lifetime. However, LEACH and it's variants are not context-aware in nature, and have limitations in case of ubiquitous and real-time health monitoring, as they do not consider any health specific component.

Synthesis: PAN coordinator selection is scenario specific, and the challenges it faces significantly depend on the scenario. The related existing algorithms finally result into random selection of PAN coordinator without considering any health or network specific components. Thus, in the proposed algorithm, we consider such aspects, and use the concept of AHP [11]–[13], to achieve a proper prioritization of the PAN-devices, in the competition of becoming the PAN coordinator of a cluster.

III. Problem Scenario

The IEEE 802.15.4 WPAN protocol has two primary options in network topology, such as the star topology and the peer-to-peer topology [14]. The selection of the topology depends on the application requirements. In this work, we consider a peer-to-peer network topology in order to enable multi-hop routing of messages from one device to other, until it reaches the sink. However, in case of peer-to-peer topology, one device must act as a PAN coordinator, which controls the association and disassociation of other devices of the network. PAN coordinator is the first device that chooses an unused PAN identifier and starts the communication through broadcasting beacon frames to neighboring devices. However, for better Quality of Service (QoS) dynamic and context-aware selection of PAN coordinator is necessary, which is addressed in the proposed work through.

We envision the PAN coordinator selection problem in the scenario of soldiers' health monitoring, where each soldier is equipped with body sensors and one single Local Processing Unit (LPU). The body sensors, such as electroencephalography (EEG) sensor, electrocardiogram (ECG) sensor, pulse oximeter, and accelerometer sense physical stimulation and dump data to the LPU associated with that particular soldier. The LPU is responsible for aggregating the sensed data, and computing health severity. We also consider this devices as hops that represent each soldier in the network. The operation area of the soldiers is generally vast, and it is not possible to enable star topology in this scenario. Therefore, we envision multi-hop routing enabled peer-to-peer topology, where the PAN coordinator behaves like the sink, and coordinates the communication within its cluster.

The real military operational fields, such as borders or valleys near by borders, are situated in extreme geographical locations, where availability of Internet is rare. Thus, inspired by the work of Cho et al. [4], we envision Flying Sensor Vehicles (FSVs) that periodically flies over the battleground, sense environmental parameters, and collect health data from the PAN coordinators as illustrated in Figure 1. The simultaneous acquisition of environmental data and soldiers' physiological data opens the door to comparative analysis of the both, to assess each soldier's sustainability in different extreme weather. To mitigate the energy consumption due to computational overhead among the LPUs, the FSVs perform necessary computations to execute the proposed $CAPCoS$ algorithm, and achieve a proper selection of the next PAN coordinators, for all soldier-clusters throughout the battlefield. One FSV dictates the LPU identification number as the next PAN coordinator to the next FSV and to the cluster members, before leaving the area of a particular soldier-cluster. We assume that the initial decision regarding the PAN coordinator selection is done before deploying the WBAN-equipped soldiers to the battlefield. We employ the concept of Analytical Hierarchy Processing (AHP) to achieve a proper ranking of the LPUs, in the run of becoming the PAN coordinator. The details of the AHP-based mathematical modeling, the considered criteria, and the proposed $CAPCoS$ algorithm, are described in the following sections.

IV. Generating Criteria Vectors

We generate three vectors – $\widetilde{AR_t}$, $\widetilde{CI_t}$, and $\widetilde{PH_t}$ of size $(n-1)$x1 each, to represent the three criteria – absorption rate (AR), cooperation index (CI), and health-priority of a soldier (PH), respectively, as discussed in the previous section. Each of these vectors represent the statistics of $(n-1)$ soldiers except the soldier who acts as the PAN coordinator in that particular turn t. In addition, we employ the concept of absorbing Markov chain [15], in order to form the vector for absorption rate (AR), i.e., $\widetilde{AR_t}$.

Let us consider the $(n-1)$ non-coordinator LPUs, or soldiers, represent the transient states of the Markov chain, and the PAN coordinator represents the absorbing state. Therefore, the probability matrix of successful packet delivery is as follows:

$$P_{suc} = \begin{pmatrix} Q & R \\ 0 & I_1 \end{pmatrix} \quad (1)$$

where,

- Q describes the transition probability of packets from one LPU to other. Therefore, Q is a $(n-1)$x$(n-1)$ matrix that represents multi-hop message routing only through the $(n-1)$ non-coordinator LPUs.
- R describes the transition probabilities from some non-coordinator LPU to the PAN coordinator, i.e., the absorbing state in the Markov chain. Therefore, R is a non-zero $(n-1)$x1 matrix.
- 0 is a 1x$(n-1)$ zero matrix.
- I_1 is a 1x1 identity matrix.

For each absorbing Markov chain, there exists a corresponding fundamental matrix $FM_{i,j}$ that represents the expected number of steps, a process needs to be in the transient state j, if it is started in the transient state i. According to the properties of absorbing Markov chain,

$$\begin{aligned} FM &= I + Q + Q^2 + ... = \sum_{m=0}^{\infty} Q^m \\ &= (I_1 - Q)^{-1} \end{aligned} \quad (2)$$

Definition 1. ***(Expected Delivery Time:)*** *The expected delivery time of an LPU is the expected duration of time in which packets from that LPU successfully reach to the PAN coordinator, through multi-hop relay.*

The expected time required by all $(n-1)$ LPUs to send a packet successfully to the PAN coordinator, at turn t, is represented by the vector $\widetilde{TR_t}$. Therefore, mathematically,

$$\widetilde{TR_t} = FM_t * \widetilde{ET_t} \quad (3)$$

$\widetilde{ET}$ represents an $(n-1)$x1 matrix or column vector, where each element indicates the time taken in the non-coordinator LPUs during message relay. Let $\alpha_{1,t}$, $\alpha_{2,t}$, ... , $\alpha_{n-1,t}$ are the time duration taken by 1^{st}, 2^{nd}, ... , $(n-1)^{th}$ LPU respectively, during message relay at turn t. Therefore, $\gamma_{i,t} = 1/\alpha_{i,t}$, denotes the successful absorption rate of i^{th} LPU, and the corresponding $(n-1)$x1 matrix or column vector $\widetilde{AR_t}$ represents the successful absorption rates of all LPUs, at turn t, as described in Algorithm 1. Thus,

$$\widetilde{AR_t} = (\gamma_{1,t}, \gamma_{2,t}, ..., \gamma_{n-1,t})^{-1} \quad (4)$$

Definition 2. ***(Cooperation Index:)*** *The Cooperation Index of an LPU is the ratio of number of packets received to number of packets transmitted by that particular LPU.*

Let, the number of packets received at i^{th} LPU is $N^i_{r,t}$, and transmitted from the i^{th} LPU is $N^i_{tr,t}$, at turn t. Therefore, the cooperation index of the i^{th} LPU ($\delta_{i,t}$), at turn t, is as follows:

$$\delta_{i,t} = \frac{N^i_{r,t}}{N^i_{tr,t}} \quad (5)$$

Thus, the cooperation index values of all $(n-1)$ LPUs, at turn t, is represented by the vector $\widetilde{CI_t}$.

$$\widetilde{CI_t} = (\delta_{1,t}, \delta_{2,t}, ..., \delta_{n-1,t})^{-1} \quad (6)$$

Definition 3. ***(Priority of Health:)*** *The Priority of Health of an WBAN-equipped soldier is a normalized metric that ranges from* 0 *to* 1*, representing the severity of physiological condition of that particular soldier.*

The health priority values of all $(n-1)$ soldiers, at turn t, is represented by the vector $\widetilde{PH_t}$ and it is computed by drawing an analogy of the concept, as discussed in one of our earlier work [1].

Algorithm 1: CAPCoS Algorithm - PAN Coordinator

Input:
- P_{suc}: Probability matrix for successful packet delivery.
- ET: Time vector representing the times taken by LPUs during packet relay, at turn t.
- The number of packets received $N^i_{r,t}$ and transmitted $N^i_{tr,t}$ by i^{th} LPU, at turn t.

Output: Criteria Vector – $\widetilde{AR_t}$

```
// Initialization
```
$Q \longleftarrow$ Matrix formed by the top $(n-1)$ rows and $(n-1)$ left columns of P_{suc}.
$R \longleftarrow$ Vector formed by the top $(n-1)$ elements of the rightmost column of P_{suc}.

```
// Fundamental Matrix Formation
```
$FM \longleftarrow (I - Q)^{-1}$.

```
// Generating Criteria Vectors
```
for $i \leftarrow 1$ ***to*** $(n-1)$ **do**
  $AR_i \longleftarrow$ From Equations 3 and 4.
  $CI_i \longleftarrow$ From Equations 5 and 6.
  $PH_i \longleftarrow$ As described in [1].

Return ($\widetilde{AR}$,$\widetilde{CI}$,$\widetilde{PH}$).

V. Context Aware Ranking

We discuss the initial part of the proposed $CAPCoS$ algorithm in the previous section in Algorithm 1. The PAN coordinator conveys these three criteria vectors to the FSV, which executes the remaining part of the algorithm.

A. Priority Vector Formation for Criteria

Each criteria has some preference over others. Otherwise, we may assume that the importance of the criteria are same. This relative preference is dynamic in nature, and may be modified in each run according to the war strategy, or other external circumstances in the battlefield. We assume, this relative preference is programmed within the FSV in the form of *pairwise comparison matrix*. The matrix elements can be changed in any turn of the FSV, in order to set different relative preference among the criteria. We term this matrix as Criteria Preference Matrix (CPM). As illustrated in Equation (7), the dimension of CPM is 3x3, as we consider three criteria in our problem scenario.

$$CPM_{ij,t} = \begin{array}{c} \\ AR \\ CI \\ PH \end{array} \begin{array}{c} \begin{array}{ccc} AR & CI & PH \end{array} \\ \begin{pmatrix} \lambda_{11,t} & \lambda_{12,t} & \lambda_{13,t} \\ \lambda_{21,t} & \lambda_{22,t} & \lambda_{23,t} \\ \lambda_{31,t} & \lambda_{32,t} & \lambda_{33,t} \end{pmatrix} \end{array} \tag{7}$$

where, $\lambda_{ij,t}$ represents the preference of criteria i over criteria j. Evidently, the preference of criteria j over criteria i is,

$$\lambda_{ji,t} = \frac{1}{\lambda_{ij,t}} \tag{8}$$

The matrix CPM is *'turn'* dependent. In different turn, the preferences among the criteria can be modified by administrator, according to their military requirement. Only the concerned authority has to change the values of λ_{ij}.

According to the concept of AHP, we need to normalize the preference matrix. Let us assume, the normalized matrix for criteria is CNM and the element of its i^{th} row and j^{th} column, at turn t, is represented as:

$$\varphi_{ij,t} = \frac{\lambda_{ij,t}}{\sum_{i=1}^{3} \lambda_{ij,t}}, \text{ such that } \sum_{i=1}^{3} \varphi_{ij,t} = 1 \tag{9}$$

Therefore, we are ready to build the 3x1 priority vector for criteria. We represent this vector as $\widetilde{CPV_t}$. The vector elements are represented as:

$$\beta_{k,t} = \frac{\sum_{j=1}^{3} \varphi_{kj,t}}{3}, \text{ such that } \sum_{k=1}^{3} \beta_{k,t} = 1 \tag{10}$$

B. Priority Vector Formation for LPUs

Along with criteria comparison, we also compare each LPU with others, depending on certain criteria. Therefore, we get different pairwise comparison matrices of LPUs for different criteria. The preference of one LPU over another means the preference of one soldier over the other. FSV

Algorithm 2: CAPCoS Algorithm - FSV

Input:
- Criteria Vectors – $\widetilde{AR_t}$, $\widetilde{CI_t}$, $\widetilde{PH_t}$
- $\lambda_{ij,t}$: Elements of Criteria Preference Matrix at turn t.

Output: Id of the PAN coordinator for next turn.

```
// Priority vector formation for criteria at turn t - CPV_t
for k ← 1 to 3 do
    β_{k,t} ⟵ (1/3) · Σ_{j=1}^{3} λ_{kj,t} / Σ_{k=1}^{3} λ_{kj,t}

// Computing total from vector elements at turn t
for i ← 1 to (n − 1) do
    AR_{tot,t} ⟵ AR_{tot,t} + AR_{i,t}.
    CI_{tot,t} ⟵ CI_{tot,t} + CI_{i,t}.
    PH_{tot,t} ⟵ PH_{tot,t} + PH_{i,t}.

// Computing individual LPU's contribution at turn t
for i ← 1 to (n − 1) do
    AR_{i,t} ⟵ AR_{i,t} / AR_{tot,t}.
    CI_{i,t} ⟵ CI_{i,t} / CI_{tot,t}.
    PH_{i,t} ⟵ PH_{i,t} / PH_{tot,t}.

// LPU preference matrices formation for three criteria at turn t
for i ← 1 to (n − 1) do
    for j ← 1 to (n − 1) do
        λ_{ij,t,AR} ⟵ AR_i / AR_j
        λ_{ij,t,CI} ⟵ CI_i / CI_j
        λ_{ij,t,PH} ⟵ PH_i / PH_j

// LPU priority vector formation for three criteria at turn t
for k ← 1 to (n − 1) do
    Compute β_{k,t,AR}.
    Compute β_{k,t,CI}.
    Compute β_{k,t,PH}.

// LPU vs. Criteria matrix formation at turn t - LCM_t
for i ← 1 to (n − 1) do
    δ_{i,1,t} ⟵ β_{i,t,AR}.
    δ_{i,2,t} ⟵ β_{i,t,CI}.
    δ_{i,3,t} ⟵ β_{i,t,PH}.

// PAN coordinator selection
FRV_t ⟵ LCM_t * CPV_t.
maxVal ⟵ The index of maximum vector element of vector FRV_t.
Return (maxVal).
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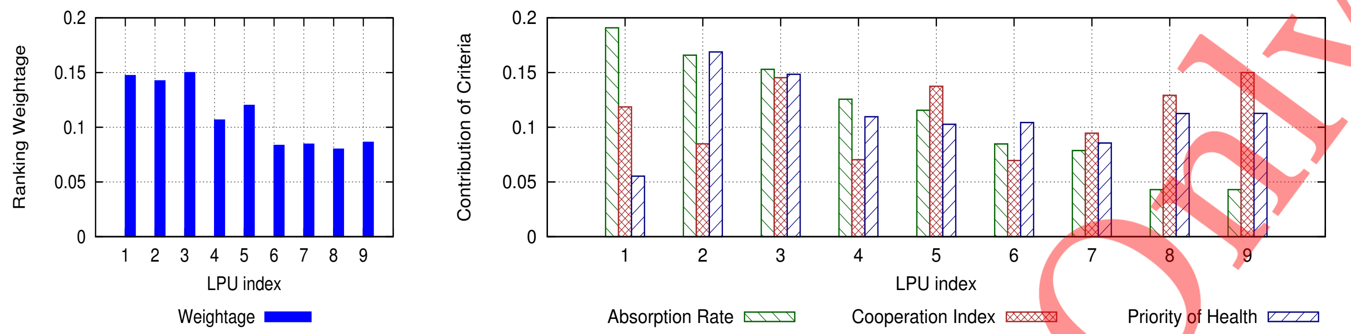


(a) Weightage of LPUs

(b) Contribution of Criteria

Fig. 2: Weightage of LPU and Contribution of Criteria

receives information from current PAN coordinator regarding the criteria values of all LPUs associated with the coordinator, and derive three different LPU Preference Matrix (LPM) for three different criteria, as illustrated in Algorithm 2.

In a similar manner, we further compute corresponding normalized matrices and finally the priority vectors. Let us consider the priority vectors for the LPUs, at turn t are – $\widetilde{LPV_{t,AR}}$, $\widetilde{LPV_{t,CI}}$, and $\widetilde{LPV_{t,PH}}$, respectively for the criteria AR, CI, and PH. The elements of vector $\widetilde{LPV_{t,AR}}$, $\widetilde{LPV_{t,SP}}$, and $\widetilde{LPV_{t,PH}}$, respectively, are represented below.

$$\beta_{k,t,AR} = \frac{1}{n-1} . \sum_{j=1}^{n-1} \frac{\lambda_{kj,t,AR}}{\sum_{k=1}^{n-1} \lambda_{kj,t,AR}}. \tag{11}$$

$$\beta_{k,t,CI} = \frac{1}{n-1} . \sum_{j=1}^{n-1} \frac{\lambda_{kj,t,CI}}{\sum_{k=1}^{n-1} \lambda_{kj,t,CI}}. \tag{12}$$

$$\beta_{k,t,PH} = \frac{1}{n-1} . \sum_{j=1}^{n-1} \frac{\lambda_{kj,t,PH}}{\sum_{k=1}^{n-1} \lambda_{kj,t,PH}}. \tag{13}$$

such that, $\sum_{k=1}^{n-1} \beta_{k,t,AR} = \sum_{k=1}^{n-1} \beta_{k,t,CI} = \sum_{k=1}^{n-1} \beta_{k,t,PH} = 1.$

C. PAN Coordinator Selection

In order to derive the final ranking of LPUs with respect to the criteria we consider in our work, we form a $(n-1)$x3 matrix in which rows represent the associated LPUs and the columns represent the three criteria. We term this matrix as LCM_t. The Final Ranking Vector at turn t is represented as:

$$\widetilde{FRV_t} = LCM_t * \widetilde{CPV_t} \tag{14}$$

We pick the index of the maximum element of vector $\widetilde{FRV_t}$, and assign the corresponding LPU as the PAN coordinator of the next turn.

VI. Analytical Result

Different existing algorithms on cluster head selection in wireless sensor networks fail to provide efficient result in case of WBANs, and turn equivalent to random cluster head selection. Moreover, criteria should be chosen according to the scenario. We choose the real-life scenario of soldiers' health monitoring in battlefield, and consider three criteria as discussed earlier.

A. Effect of Criteria

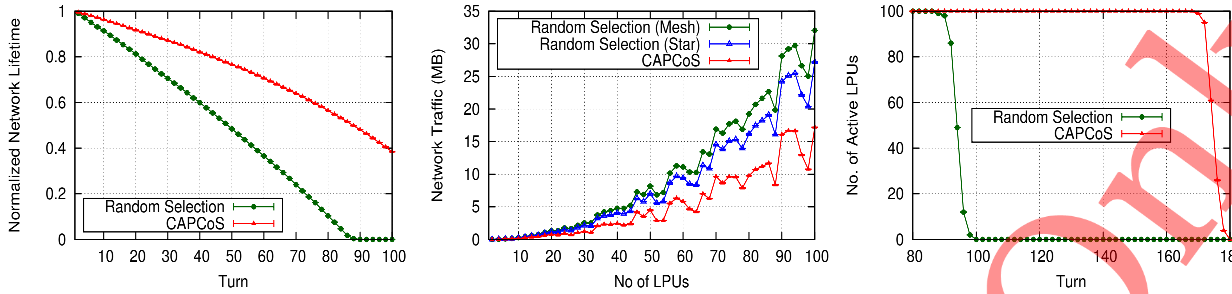
Absorption rate, cooperation index, and priority of health are the three criteria we consider in this work. The criteria preference matrix we employ in our analytics is given below.

$$CPM = \begin{array}{c} \\ AR \\ CI \\ PH \end{array} \begin{array}{c} \begin{matrix} AR & CI & PH \end{matrix} \\ \begin{pmatrix} 1 & 2 & 3 \\ \frac{1}{2} & 1 & 2 \\ \frac{1}{3} & \frac{1}{2} & 1 \end{pmatrix} \end{array} \tag{15}$$

Figure 2 illustrates the final ranking after simulating an experiment with 10 LPUs. From Figure 2(a) it is evident that the 3^{rd} LPU has the highest weightage, therefore, CAPCoS selects this LPU as the PAN coordinator for next run. Figure 2(b) depicts the criteria-wise contribution of each LPU, where evidently the 3^{rd} LPU shows considerable amount of contribution in each criteria. Among the other close competitor 1^{st}, 2^{nd}, and 5^{th} LPUs are notable. However, priority of health and cooperation index is very low in case of 1^{st} and 2^{nd} LPU respectively, and between 3^{rd} and 5^{th} LPU, the prior is the comparatively better choice. While computing the absorption rate of each LPU through the properties of absorbing Markov chain, we consider the transmission range as 2 hops with success probability 0.8.

B. Network Performance

We compare the proposed CAPCoS algorithm with random selection of PAN coordinator, and we show that CAPCoS is the better choice if we analyze the network perspectives of the system. The network parameters and the corresponding values we consider in our work, are summarized in Table I.



(a) Normalized Network Lifetime (b) Network Traffic vs. LPU count (c) No. of Active LPUs after each turn

Fig. 3: Comparison

TABLE I: Simulation Setup

Parameter	Value
LPU count	100
Number of turns	200
Initial energy of each LPU	1 J
Energy dissipation due to initial broadcast	1-5 mJ
Energy dissipation due to computation	1-5 mJ
Energy dissipation due to final broadcast	1-5 mJ
Average packet length	500 B

Figure 3 briefly illustrates the effectiveness of CAPCoS from network point of view. We simulate experiments to analyze the network lifetime of CAPCoS. Figure 3(a) clearly shows that CAPCoS has approximately twice bigger network lifetime than general random selection techniques. The involvement of Flying Sensor Vehicle (FSV) is responsible for this bigger lifetime. FSV manages the necessary complex computation and broadcasts the LPU id of the selected PAN coordinator to other LPUs, before leaving the cluster, and thus, saving considerable amount of energy. Figure 3(b) depicts the increasing network traffic with the increment of LPU count. We compare the network traffic of CAPCoS with both star and mesh topologies in case of random selection. CAPCOS generates less number of packets with respect to the other two options. Therefore, network traffic is comparatively less in the proposed system. Figure 3(c) shows the activity status of LPUs after each turn. In case of general random selection after 90 turns the LPUs start becoming dead, whereas in case of CAPCoS this incident occurs after 170 turns. This result also validates our claim regarding the better network lifetime of CAPCoS, over random selection of PAN coordinator.

VII. Conclusion

In this paper, we proposed an context-aware algorithm that selects a PAN coordinator periodically based on the network characteristics, and health status of each soldier. FSVs overcome the problems of limited infrastructure in border areas, and makes the defence stronger by making context-aware war strategies. We compared the CAPCoS algorithm with random selection of PAN coordinator, and verified that the prior has better network lifetime with less network traffic. In future, we plan to consider multi-layer hierarchical framework of battlefield monitoring, and hybrid cluster formation among the soldiers along with inter-cluster network communication.

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