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The Connectivity of Selfish Wireless Networks

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ABSTRACT The network connectivity of selfish wireless networks (SeWNs) constituted by selfish nodes (SeNs) is investigated. The SeN's degree of node-selfishness (DeNS) is used for characterizing the effects of its energy resources and the benefits of the incentives provided for enhancing its transmission willingness. Furthermore, the SeNs' signal to interference plus noise ratios are defined in terms of both their DeNSs and their interference factors. We then continue by quantifying the effect of node-selfishness on the grade of network connectivity and derive both the upper and lower bounds of the critical DeNS. Explicitly, the network is deemed to be connected when the DeNS is below the lower bound and unconnected for a DeNS above the upper bound. This allows us to quantify the asymptotic critical DeNSs for our SeWNs. In addition, we develop an energy-conscious node-selfishness model for characterizing the relationship between the SeN's residual energy and its DeNS. Based on this model and on the asymptotic critical DeNS derived, the critical amount of residual energy required for maintaining a specific grade of network connectivity is determined, which is verified by our simulation results.

INDEX TERMS Network connectivity, selfish wireless network, percolation theory, node-selfishness, energy resource.

I. INTRODUCTION

Maintaining connectivity within a wireless network is the prerequisite for guaranteeing efficient networking relying on the functions of routing, power control, topology control, etc. Given the proliferation of smart devices in intelligent networks, each node is expected to be endowed with smart autonomic functions. By instinct, the individual network nodes would prefer to act selfishly rather than altruistically in distributed network scenarios. For instance, while forwarding the packets of other nodes at the cost of sacrificing their own limited resources, they expect to satisfy some of their own objectives, such as maximizing their own transmission rate and/or minimizing their own resource consumption. A wireless network which consists of nodes exhibiting a selfish behavior is hence referred to as a selfish wireless network (SeWN). In such network scenarios, the selfish behavior of network nodes may reduce the throughput of the nodes and/or their integrity, thus potentially leading to a degraded network connectivity.

The management of node-selfishness has been widely investigated [1]–[7]. For example, the detection regime of selfish nodes (SeNs) was investigated in [1] by relying on a low-complexity sliding-window aided non-parametric cumulative sum-rate maximization protocol, while a novel "node-selfishness" detection approach was proposed in [2] for assisting the SeNs to efficiently exploit the available channels. Furthermore, with the objective of stimulating the willingness of the SeNs to cooperatively relay messages, an efficient and fair incentive mechanism was conceived in [3]. A range of resource-exchange-based incentive mechanisms were advocated in [4] with the same objective, while in [5] a double-auction-based user-assignment scheme was studied. Additionally, in order to enforce "genuine truth-telling" for the SeNs, several strategy-proof approaches were conceived in [6] for finding trusted routers. Finally, the d'Aspremont and Gerard-Varet approach was employed in [7] for improving the entire network's performance. The viability of the aforementioned schemes relied on the assumption that at least one route existed between any two nodes in the SeWNs considered.

The connectivity of wireless networks has attracted substantial research attention. A matrix-decomposition aided method was provided in [8] for deriving an expression for the probability of a k-connected[1] vehicular *ad hoc* network. The network's connectivity was enhanced by the open-access algorithm of [9] and by the tree-cluster-based data-gathering algorithm [10]. The necessary conditions of the network connectivity were detailed in [11] and [12] by investigating both the number of isolated nodes and the boundary effects of a network. The node's critical transmit power was determined in [13], which was sufficient for guaranteeing the network connectivity, subject to the level of the maximum tolerable mutual interference. The connectivity of homogeneous ad hoc networks has been widely studied with the aid of percolation theory[2] [14]. The sufficient and necessary conditions of the network connectivity were detailed in [15] by studying both the outer and inner bounds on the connectivity region with the aid of percolation theory. The connectivity of dynamic wireless networks was studied in [16] and [17] both with the aid of continuum percolation theory [18] and by relying on ergodic stochastic processes[3] [19]. The impact of interference imposed by the imperfect orthogonality of spreading codes in the code division multiple access (CDMA) on the connectivity was studied in the context of large-scale ad hoc networks based on percolation theory in [20], where the critical interference level increased inverse-proportionally with the node-density. All the above-mentioned contributions assumed that the network nodes were unselfish and hence would altruistically cooperate for the sake of forwarding the packets of other nodes. By contrast, the connectivity of SeWNs was investigated in [21], but the detrimental effects of node-selfishness and the mutual interference amongst the nodes routinely imposed by resource sharing were neglected.

Against this background in this paper, we will investigate the effect of node-willingness on the network's grade of connectivity. In order to characterize the effects of both the SeN's energy resources and the benefits of incentives on its node-selfishness, we define the degree of node-selfishness (DeNS) for quantifying the node's willingness of cooperatively transmitting packets. Furthermore, we also define the SeNs' signal to interference plus noise ratios (s-SINR) at their receivers as the functions of their DeNSs, which play an important role in quantifying the effects of the node-selfishness on the grade of network connectivity.

The main contributions of this paper are as follows:

1) We derive both the upper and lower bounds of the DeNS in SeWNs with the aid of percolation theory. The network is said to be connected, when the DeNS is below the lower bound; and it is deemed to be unconnected, when the DeNS is above the upper bound.
2) The critical value of the DeNS is determined, as the node density tends to infinity and simultaneously the interference factor (InF) tends to zero.
3) We develop an energy-conscious node-selfishness model for characterizing the effects of both the SeN's residual energy and the specific incentive received on the DeNS. Furthermore, we determine the critical amount of residual energy, above which the network connectivity is guaranteed with a certain probability.

The remainder of this paper is organized as follows. Our system model is introduced in Section II. Section III investigates the SeWN's connectivity with the aid of percolation theory. Section IV details the connectivity of the SeWN under an energy-conscious node-selfishness model. Our simulation results are provided in Section V, while Section VI concludes this paper.

II. SYSTEM MODEL

In SeWNs, the presence or absence of connection between a pair of SeNs is affected both by their node-selfishness and by the channel attenuation, as well as by the interference imposed by other nodes. Accordingly, we define both the bidirectional link connectivity of these two SeNs and the probability of being connected for the sake of characterizing the network connectivity of SeWNs.

A. THE NODE-SELFISHNESS MODEL

An SeWN is characterized by a graph $\mathcal{G}(\mathcal{V}, \mathcal{E})$, where $\mathcal{V}$ is the set of SeNs and $\mathcal{E}$ is the set of all connected bidirectional links amongst the SeNs in $\mathcal{V}$. In order to forward the packets in such an SeWN, at least one adequately connected route is required, which consists of several links. When forwarding packets through a specific link, an SeN which has successfully received the packets might decide to behave selfishly by refusing to altruistically forward these packets, for example, owing to its limited available resources denoted by Υ. In order to circumvent this problem, an incentive denoted by Ξ might be offered to the SeN for stimulating its packet-forwarding inclination. Accordingly, both the SeN's available resources Υ and its received incentive Ξ directly affect its willingness to forward the packets and hence they also affect the specific link's state of connection, which is either "on" or "off". Explicitly, the link's "on" or "off" state is affected by its selfish/altruistic behavior, despite the fact that the physical link may be of high quality. Specifically, the SeN's DeNS is defined as follows.

Definition 1 (DeNS): The SeN's DeNS, denoted by $S(\Upsilon, \Xi)$ quantifies the effects of both its available resources Υ and that of the incentive Ξ influencing its selfish/altruistic behavior, which spans from 0 (altruistic) to 1 (completely selfish), i.e., we have $0 \leq S(\Upsilon, \Xi) \leq 1$.

From *Definition 1*, the SeN's DeNS depends on both its available resources Υ and the incentive Ξ received. When the SeN's available resources Υ are abundant, its DeNS $S(\Upsilon, \Xi)$ is close to 0, while if the SeN's available resources Υ are close to the minimum, its DeNS $S(\Upsilon, \Xi)$ may get close to 1. Hence, the SeN's DeNS $S(\Upsilon, \Xi)$ increases, as its available resources Υ become depleted. To elaborate a little further, for a fixed amount of available resources Υ, the DeNS $S(\Upsilon, \Xi)$

[1] Being k-connected implies that given a graph associated with a set of nodes, any node is connected to at least k closest neighbors in this graph.

[2] Percolation theory describes the behavior of connected clusters in a random graph.

[3] An ergodic stochastic process has the same behavior averaged over time as averaged over the space of all the system's states.

decreases, as the incentive Ξ is increased. For the sake of compactness, we use S and $S(\Upsilon, \Xi)$ interchangeably to denote the SeN's DeNS, unless this might lead to ambiguity.

B. POISSON POINT PROCESS

In this subsection, we introduce both the classic point process (PP) [22] and the Poisson point process (PPP) for modeling the location of the nodes in our SeWN. A PP represents a mapping Φ from a probability space to a space of points marking the node-location, which is formally stated as $\Phi : \Omega \to \mathcal{N}$, where Ω is the set of possible outcomes in $\mathbb{R}^d$ and $\mathcal{N}$ is the set of point sequences in $\mathbb{R}^d$. Furthermore, a PPP having the average point density of λ is the PP, where the number of points in any unit-size area is Poisson distributed with a density of λ. A PPP has the following two properties: the number of points in disjoint sets is independent of each other; furthermore, the number of points in any set is a Poisson-distributed random variable. We classify the SeWN into homogeneous and inhomogeneous SeWNs in terms of the SeNs' DeNS. In homogeneous scenarios, all SeNs possess the same DeNS. By contrast, in inhomogeneous scenarios, different SeNs exhibit different values of DeNS. Since all SeNs behave independently of each other, the PPP of the inhomogeneous SeNs having dissimilar DeNSs can be regarded as the superposition of the PPPs of the SeNs possessing the same DeNS. Hence, an inhomogeneous SeWN can be decomposed into several homogeneous SeWNs, whose connectivity may then be determined in parallel. Therefore, the connectivity of the homogeneous SeWN provides insight into the connectivity characteristics of an inhomogeneous SeWN. Accordingly, we focus our attention on the connectivity of homogeneous SeWNs.

C. THE PATHLOSS MODEL

In the SeWN, the pathloss of the link between node u and node v is expressed as $l(\| x_v - x_u \|)$, where x_u and x_v are the corresponding node locations, and $\| x_v - x_u \|$ is the Euclidean distance between node u and node v. Let p_u denote the transmit power of SeN $u \in \mathcal{V}$, which is within a given range $[0, P]$, with P being the maximum affordable transmit power. The sufficient and necessary condition for ensuring that the aggregate received power $\sum_{u\in\mathcal{V}, u\neq v} p_u l(\| x_v - x_u \|)$ at node v is almost surely (a.s.) finite is given by [23]

$$\int_D^\infty l(t)tdt < \infty \tag{1}$$

for a sufficiently large value of the distance D between node v and u ($\forall v, u \in \mathcal{V}, u \neq v$). The most common pathloss model $l(t)$ is $l(t) = t^{-\sigma}$, with the pathloss exponent σ ranging from 3 to 6. In this paper, we assume the channel attenuation to be a non-increasing isotropic function, which has the following additional properties [20]:

$$l(\| x_v - x_u \|) = 0, \quad \text{s.t.} \ \| x_v - x_u \| \geq \rho, \tag{2}$$

$$\frac{\zeta N_0}{P} < l(\| x_v - x_u \|) < M, \quad \text{s.t.} \ \| x_v - x_u \| \leq \delta, \tag{3}$$

for $\forall x_v, x_u \in \mathbb{R}^2$, $0 < \delta < \rho$ and $PM > \zeta N_0$, where ρ is the minimum distance of the nodes u and v required for ensuring that the power received at node v is deemed to become negligible, namely $Pl(\| x_v - x_u \|) \approx 0$. By contrast, δ is the maximum effective distance of the nodes u and v, over which the transmitted signal of node u cannot be successfully received at node v. Furthermore, M is the maximum channel attenuation value, N_0 is the power of the thermal noise and ζ is the threshold to be exceeded at the receiver of node v for ensuring successful detection.

D. BIDIRECTIONAL LINK CONNECTION

In this subsection, we scrutinize the connectivity of the link uv spanning from node u to node v. In an altruistic network, the signal power received at node v from node u is formulated as $p_u l(\| x_v - x_u \|)$. Nevertheless, since the DeNS affects its transmit power earmarked for forwarding packets, node u reduces its transmit power p_u according to $(1 - S_u)$, thus its final signal power received at node v from node u can be expressed as $p_u l(\| x_v - x_u \|)(1 - S_u)$. Additionally, the connectivity of the link is also affected by the interference imposed by other nodes, for instance, owing to the imperfect orthogonality of the spreading codes used in CDMA [24].

Below we introduce the formal definition of the s-SINR, which is similar to the definition of the traditional SINR.

Definition 2 (s-SINR): The s-SINR of the link spanning from node u to node v is jointly affected by the DeNS, by the pathloss and by the total amount of interference imposed by other SeNs, which is formulated as

$$s\text{-SINR}_{uv} = \frac{p_u(1 - S_u)l(\| x_u - x_v \|)}{N_0 + \gamma \sum\limits_{k\neq u,v} p_k(1 - S_k)l(\| x_k - x_v \|)}, \tag{4}$$

where γ is the InF.[4]

Naturally, when the value of $s\text{-SINR}_{uv}$ is above the successful-detection threshold ζ, the signal received from node u can indeed be successfully detected by node v. Given the definition of s-SINR, the bidirectional link connection is defined as follows.

Definition 3 (Bidirectional Link Connectivity): The connectivity of a bidirectional link $\overline{uv}$ is defined as a Boolean variable $\mathcal{B}_{\overline{uv}}$, formulated as

$$\mathcal{B}_{\overline{uv}} = \begin{cases} 1, & \text{if } s\text{-SINR}_{uv} \geq \zeta \text{ and } s\text{-SINR}_{vu} \geq \zeta \\ 0, & \text{otherwise} \end{cases} \tag{5}$$

where the logical 1 implies that the bidirectional link $\overline{uv}$ is indeed "on", i.e., connected, and 0 means that the bidirectional link $\overline{uv}$ is "off", i.e., unconnected.

Based on *Definition 3*, the bidirectional link $\overline{uv}$ is said to be connected, if the signals transmitted from node u to v and from node v to u are both successfully detected.

[4]The InF of γ ($0 \leq \gamma \leq 1$) quantifies the level of mutual-interference imposed by the resource reuse. For instance, this might be imposed by the imperfect orthogonality of the spreading codes used in CDMA and hence it is related to the frequency reuse factor. For example, $\gamma = 0$ represents that the spreading codes used by different nodes are completely orthogonal. By contrast, $\gamma = 1$ implies that the same spreading code is reused in the immediate vicinity.

The SeWN $\mathcal{G}(\mathcal{V}, \mathcal{E})$, which contains the bidirectional link $\overline{uv}$, is further formulated as $u, v \in \mathcal{V}$ and $\mathcal{E} = \{\overline{uv} : \mathcal{B}_{\overline{uv}} = 1\}$. For convenience, we define the *link-connectivity component (LCC)* as

$$\mathcal{K}(x) = \{y \in \mathcal{V} : \exists x \leftrightsquigarrow y\}, \quad (6)$$

where $x \leftrightsquigarrow y$ represents a bidirectional path between node x and node y. An example is shown in Fig. 1, where a bidirectional path exists between node 1 and node 4, i.e., we have $1 \leftrightsquigarrow 4$. Furthermore, nodes 2 and 3 are also connected with node 1, thus the LCC of node 1 is $\mathcal{K}(1) = \{2, 3, 4\}$, and its cardinality is $|\mathcal{K}(1)| = 3$.

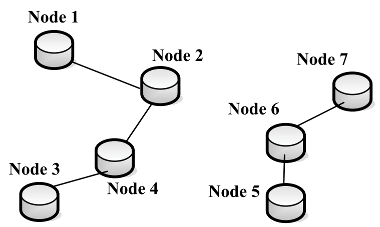

FIGURE 1. An example of network topology for interpreting the LCC, $|\mathcal{K}(1)| = |\mathcal{K}(2)| = |\mathcal{K}(3)| = |\mathcal{K}(4)| = 3$ and $|\mathcal{K}(5)| = |\mathcal{K}(6)| = |\mathcal{K}(7)| = 2$.

The bidirectional connection of each link in the path depends on the s-SINRs of the corresponding receivers. Observe in Eq. (4) that the s-SINR of the received signal is related to the pathloss, to the number of interferers, as well as to the InF γ and to the DeNS S. Additionally, both the pathloss between two adjacent nodes and the number of interferers are determined by the node density λ. For instance, as the node-density increases, the average distance or pathloss between two adjacent nodes decreases, and this also increases the average number of interferers. Hence, the node density λ can be used as the common parameter to characterize both the effects of the pathloss and of the average number of interferers. As a result, we claim that the s-SINR is related to both the node density λ, to the InF γ as well as to the DeNS S. Accordingly, given an s-SINR threshold ζ in Eq. (5), the LCC $\mathcal{K}(x)$ defined in Eq. (6) is a function of the triplet (λ, γ, S). Following from the percolation theory of [17], a simple measure of the network connectivity is given by the maximum cardinality of all LCCs ($\mathcal{K}(x), \forall x \in \mathcal{V}$) in the SeWN. This is rooted in the fact that an SeN in the LCC of higher cardinality is capable of communicating with more SeNs, which are generally distributed across a wider area of the SeWN, thus potentially enhancing the network connectivity. From this perspective, the LCC of infinite cardinality (i.e., infinite size) implies the network connectivity of large-scale networks, where the number of nodes tends to infinite. Hence, we define the connectivity probability of the large-scale SeWN as follows.

Definition 4 (Connectivity Probability of Large-Scale SeWNs): The connectivity probability of our SeWN is defined as the probability that there exists an LCC of infinite size, expressed as[5]

$$\mathcal{P}(\lambda, \gamma, S) = \mathbb{P}\left(|\mathcal{K}(x)| = \infty, \forall x \in \mathcal{V}\right), \quad (7)$$

where $\mathbb{P}(\cdot)$ is the probability operator.

Since the LCC $\mathcal{K}(x)$ is a function of the triplet (λ, γ, S), the connectivity probability $\mathcal{P}(\lambda, \gamma, S)$ of *Definition 4* is a function of the triplet (λ, γ, S) as well. Furthermore, $\mathcal{P}(\lambda, \gamma, S) = 0$ implies that there is no infinite-size LCC, and $\mathcal{P}(\lambda, \gamma, S) > 0$ implies that there may exist an infinite-size LCC with a certain probability. Nevertheless, when the SeWN includes a large number of nodes, it becomes a challenge to compute the probability $\mathbb{P}\left(|\mathcal{K}(x)| = \infty, \forall x \in \mathcal{V}\right)$, hence it is difficult to determine the exact expression of the connectivity probability $\mathcal{P}(\lambda, \gamma, S)$ with the triplet (λ, γ, S).

In the following sections we focus our attention on determining whether the SeWN is connected or not, while neglecting the exact expression of $\mathcal{P}(\lambda, \gamma, S)$ with the triplet (λ, γ, S). In order to facilitate our further analysis, let us reformulate our SeWN $\mathcal{G}(\mathcal{V}, \mathcal{E})$ as $\mathcal{G}(\lambda, \gamma, S)$.

III. CONNECTIVITY OF SeWNs

In this section, we first introduce the concept of connectivity region in the SeWN $\mathcal{G}(\lambda, \gamma, S)$ and then derive the upper and lower bounds of the network connectivity of SeWNs. Finally, a pair of critical DeNSs is obtained for different SeWN scenarios.

A. CONNECTIVITY REGION

Again, the network connectivity of the SeWN $\mathcal{G}(\lambda, \gamma, S)$ is affected by the node density λ, the InF γ and the DeNS S. We hence formally define the connectivity region of the SeWN in terms of the parameter space $\mathbb{S}(\lambda, \gamma, S)$, which is represented by a specific set of the parameter triplets (λ, γ, S). Explicitly, the connectivity region $\mathcal{C}$ is defined as the particular set of the parameter triplets (λ, γ, S), for which there may exist an infinite-size LCC in $\mathcal{G}(\lambda, \gamma, S)$, and we have

$$\mathcal{C} = \{(\lambda, \gamma, S) : \mathcal{P}(\lambda, \gamma, S) > 0\} \subseteq \mathbb{S}(\lambda, \gamma, S), \quad (8)$$

where $\mathcal{P}(\lambda, \gamma, S)$ was defined in Eq. (7). There are two basic properties of the connectivity region in such SeWNs (cf. [15, Th. 1]). 1) The connectivity region $\mathcal{C}$ is contiguous, which implies that there exists at least one path in $\mathcal{C}$ connecting any two points $(\lambda_1, \gamma_1, S_1), (\lambda_2, \gamma_2, S_2) \in \mathcal{C}$. This property can be shown to hold with the aid of the coupling property[6] of [18]; 2) Almost surely there exists either no

[5]In *Definition* 4, we have defined the connectivity probability of the large-scale SeWN (cf. [25]). However, we may also appropriately adapt this definition to a finite-scale network. Explicitly, the connectivity probability of a finite-scale network is given by the probability that any two nodes are connected to each other, which is formulated as $\mathcal{P}(\lambda, \gamma, S) = \mathbb{P}\left(|\mathcal{K}(x)| = |\mathcal{V}|, \forall x \in \mathcal{V}\right)$, where $|\mathcal{V}|$ is the total number of nodes in this finite-scale network.

[6]In probability theory, coupling refers to the construction of different models over the same probability space in some sensible way, in order to directly compare the models. For example, let X_1 and X_2 be two random variables defined over the probability spaces ω_1 and ω_2. Then a coupling of ω_1 and ω_2 is a new probability space ω over which there are two random variables Y_1 and Y_2 such that Y_1 has the same distribution as X_1, while Y_2 has the same distribution as X_2.

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infinite-size LCC or a single unique infinite-size LCC in $\mathcal{G}(\lambda, \gamma, S)$, which follows from the properties of ergodic stochastic processes [19].

B. CONNECTIVITY OF SELFISH NETWORKS

In the preceding subsection, the connectivity region $\mathbb{S}(\lambda, \gamma, S)$ has been defined for employment in investigating the network connectivity of SeWNs. When the parameter triplet (λ, γ, S) is within the connectivity region $\mathcal{C}$, the corresponding SeWN $\mathcal{G}(\lambda, \gamma, S)$ is connected with a certain probability. By contrast, having a parameter triplet (λ, γ, S) outside the connectivity region $\mathcal{C}$ implies that the SeWN remains unconnected. Hence, the critical surface $SF(\lambda, \gamma, S)$ defining the boundary of this connectivity region separates the parameter space $\mathbb{S}(\lambda, \gamma, S)$ into two parts, namely the connectivity region associated with $\mathcal{P}(\lambda, \gamma, S) > 0$ and the unconnected region having $\mathcal{P}(\lambda, \gamma, S) = 0$. In this paper, our objective is to determine the critical surface $SF(\lambda, \gamma, S)$ for characterizing the network connectivity, but determining the exact expression of the connectivity probability $\mathcal{P}(\lambda, \gamma, S)$ with the triplet (λ, γ, S) is beyond the scope of this contribution.

For example, as the DeNS S increases, some of the previously connected bidirectional links may become broken according to Eqs. (4) and (5), hence the connectivity of the SeWN $\mathcal{G}(\lambda, \gamma, S)$ may be jeopardized for $S < 1$. Specifically, an altruistic network $\mathcal{G}(\lambda, \gamma, 0)$ retains its connectivity for a sufficiently high node density λ, provided that the InF obeys $\gamma < \gamma^*(\lambda)$, with $\gamma^*(\lambda)$ being the critical value of the InF γ in [20]. By contrast, in the extremely selfish scenario of $\mathcal{G}(\lambda, \gamma, 1)$, none of the nodes are capable of communicating with each other. Hence, these parameter triplets $(\lambda, \gamma^*(\lambda), 0)$ belong to the critical surface $SF(\lambda, \gamma, S)$. For the sake of determining the critical surface $SF(\lambda, \gamma, S)$, we provide *Proposition* 1 below.

Proposition 1: For the connectivity of the SeWN, the problem of finding the critical surface $SF(\lambda, \gamma, S)$ is equivalent to finding the critical InF $\gamma^*(\lambda, S)$ quantifying the maximum tolerable interference level or finding the critical DeNS $S^*(\lambda, \gamma)$ from a node-selfishness point of view.

Proof: Please refer to Appendix A. ∎

Based on *Proposition 1*, whether the SeWN is connected or not is determined in terms of the *critical InF* $\gamma^*(\lambda, S)$ or the *critical DeNS* $S^*(\lambda, \gamma)$. Given λ and S, if we have $\gamma < \gamma^*(\lambda, S)$, the SeWN $\mathcal{G}(\lambda, \gamma, S)$ is connected with a certain probability, otherwise, it is unconnected. Likewise, given λ and γ, if we have $S < S^*(\lambda, \gamma)$, the SeWN $\mathcal{G}(\lambda, \gamma, S)$ is connected with a certain probability, otherwise, it is unconnected.

1) ASYMPTOTIC CRITICAL InF

Without loss of generality, we consider the SeWN $\mathcal{G}(\lambda, \gamma, S)$, where all SeNs are homogeneous and have the same DeNS S. From *Definition 2*, the s-SINR$_{uv}$ is rewritten as

$$s\text{-SINR}_{uv} = \frac{p_u l(\| x_u - x_v \|)}{\frac{N_0}{(1-S)} + \gamma \sum\limits_{k \neq u,v} p_k l(\| x_k - x_v \|)}. \tag{9}$$

By employing the result of [20, Th. 4], we arrive at the following result. When we have $\lambda \to \infty$ and $S \to 0$, the asymptotic behavior of the critical InF is encapsulated into[7]

$$\gamma^*(\lambda, S) = \Theta\left(\frac{1}{\lambda(1-S)}\right). \tag{10}$$

When the InF is less than its critical InF value, i.e., $\gamma < \gamma^*$, the SeWN is connected with a certain probability. Otherwise, it is unconnected. Avoiding the violation of the critical InF $\gamma^*(\lambda, S)$ is used for guiding and informing the interference-based design of the system for maintaining the connectivity of the SeWN.

2) UPPER AND LOWER BOUNDS OF THE CRITICAL DeNS

Let us investigate the network connectivity from a node-selfishness perspective, and determine both the upper bound $S^u(\lambda, \gamma)$ and the lower bound $S^l(\lambda, \gamma)$ of the critical DeNS in the SeWN $\mathcal{G}(\lambda, \gamma, S)$ with the aid of percolation theory so that the critical DeNS S^* satisfies $S^l(\lambda, \gamma) \le S^*(\lambda, \gamma) \le S^u(\lambda, \gamma)$. For any S ensuring that $0 \le S \le S^l(\lambda, \gamma)$, there exists an LCC of infinite size in the SeWN $\mathcal{G}(\lambda, \gamma, S)$, i.e., we have $\mathcal{P}(\lambda, \gamma, S) = 1$. For any S satisfying that $S^u(\lambda, \gamma) \le S \le 1$, there is only a limited number of LCCs of finite size in the SeWN $\mathcal{G}(\lambda, \gamma, S)$, i.e., we have $\mathcal{P}(\lambda, \gamma, S) = 0$. The upper and lower bounds of the critical DeNS are provided by the following pair of theorems.

Theorem 1 (Lower Bound of the Critical DeNS): For a sufficiently high node density λ, as $\lambda \to \infty$ and $\gamma \le \frac{1}{12M\lambda\rho^2(1+\varepsilon)}\left(\frac{\psi(\lambda)}{\zeta} - \frac{N_0}{P}\right)$ with $\varepsilon > 0$, the lower bound of the critical DeNS is shown to be

$$S^l(\lambda, \gamma) = 1 - \frac{\zeta N_0}{P\psi(\lambda) - 12\lambda\zeta\gamma PM\rho^2(1+\varepsilon)}, \tag{11}$$

where $\psi(\lambda)$ denotes the pathloss of the link which is a monotonically increasing function of the node density λ, where we have $\lim\limits_{\lambda\to\infty} \psi(\lambda) = M$.

Proof: Please refer to Appendix B. ∎

Theorem 2 (Upper Bound of the Critical DeNS): For a node density of $\lambda > \frac{16PM}{(1-\varepsilon)N_0\zeta\delta^2}$ and an InF of $\gamma \le \frac{8PM - 8N_0\zeta}{(1-\varepsilon)\zeta^2\lambda\delta^2 N_0 - 16PM\zeta}$ with $\varepsilon > 0$, the upper bound of the critical DeNS obeys

$$S^u(\lambda, \gamma) = 1 - \frac{8N_0\zeta}{8PM(1+2\zeta\gamma) - (1-\varepsilon)\lambda\gamma N_0\zeta^2\delta^2}. \tag{12}$$

Proof: Please refer to Appendix C. ∎

We have determined both the upper and lower bounds of the critical DeNS with the aid of percolation theory [18]. This was achieved by mapping the SeWN $\mathcal{G}(\lambda, \gamma, S)$ onto a discrete lattice $\mathcal{L}$, as shown in Fig. 2 and by assuming that we have an open edge[8] for the discrete lattice in terms of the s-SINR of any node in the SeWN $\mathcal{G}(\lambda, \gamma, S)$.

[7] Knuth's notation [26] is used throughout the paper: $f(z) = \Theta(h(z))$ iff there exist a sufficiently large z_0 and two positive constants c_1^* and c_2^*, so that for any $z > z_0$, we have $c_1^* h(z) \ge f(z) \ge c_2^* h(z)$.

[8] The open edge of a discrete lattice is defined in Appendix C.

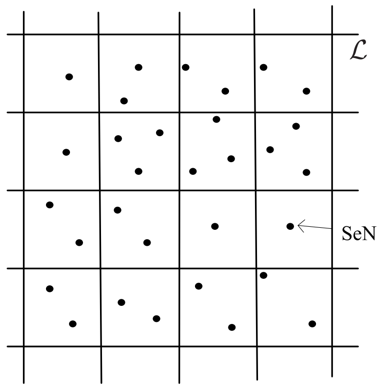

FIGURE 2. **Mapping the SeWN $\mathcal{G}(\lambda, \gamma, S)$ onto the discrete lattice $\mathcal{L}$.**

If we have $S \leq S^l(\lambda, \gamma)$, there exists an infinite-length path comprised of open edges in a discrete lattice, thus leading to a connected SeWN with $\mathcal{P}(\lambda, \gamma, S) = 1$. By contrast, if $S \geq S^u(\lambda, \gamma)$, there are only finite-length paths in the corresponding discrete lattice, thus leading to a unconnected SeWN, namely its connectivity probability $\mathcal{P}(\lambda, \gamma, S) = 0$.

In the next subsection, the upper and lower bounds of the critical DeNS are considered, which have to be satisfied for maintaining the network connectivity in the SeWN $\mathcal{G}(\lambda, \gamma, S)$.

3) ASYMPTOTIC CRITICAL DeNS

In this subsection, we determine the critical DeNS $S^*(\lambda, \gamma)$ that has to be satisfied for maintaining the connectivity of the SeWN according to the upper bound $S^u(\lambda, \gamma)$ and the lower bound $S^l(\lambda, \gamma)$ of the critical DeNS. The sufficient condition for maintaining the network connectivity in the SeWN $\mathcal{G}(\lambda, \gamma, S)$ is $S < S^l(\lambda, \gamma)$, since the node density λ is sufficiently high and the InF is sufficiently low, obeying $\gamma \leq \frac{1}{12M\lambda\rho^2(1+\varepsilon)}\left(\frac{\psi(\lambda)}{\zeta} - \frac{N_0}{P}\right)$, as stated in *Theorem 1*. By contrast, the necessary condition for the connectivity of this SeWN $\mathcal{G}(\lambda, \gamma, S)$ is $S < S^u(\lambda, \gamma)$, since we have $\lambda > \frac{16PM}{(1-\varepsilon)N_0\zeta\delta^2}$ and $\gamma \leq \frac{8PM-8N_0\zeta}{(1-\varepsilon)\zeta^2\lambda\delta^2N_0-16PM\zeta}$, as stated in *Theorem 2*.

From the pathloss model of Eqs. (2) and (3), we have $N_0\zeta < PM$ and $\delta^2 < \rho^2$, and hence we readily obtain $(1-\varepsilon)\lambda\gamma N_0\zeta^2\delta^2/8 < 12\lambda\zeta\gamma PM\rho^2(1+\varepsilon)$, which leads to $PM(1+2\zeta\gamma) - (1-\varepsilon)\lambda\gamma N_0\zeta^2\delta^2/8 > P\psi(\lambda) - 12\lambda\zeta\gamma PM\rho^2(1+\varepsilon)$. By comparing Eqs. (11) and (12), we arrive at $S^l(\lambda, \gamma) < S^u(\lambda, \gamma)$, which implies that there exists a critical DeNS $S^*(\lambda, \gamma)$, so that we have $S^l(\lambda, \gamma) \leq S^*(\lambda, \gamma) \leq S^u(\lambda, \gamma)$.

Theorem 3 (Asymptotic Critical DeNS): For the node density of $\lambda \to \infty$ and the InF $\gamma \to 0$, the critical DeNS obeys the following asymptotic behavior

$$S^*(\lambda, \gamma) = 1 - \frac{1}{\frac{PM}{N_0\zeta} - \Theta(\lambda\gamma)}. \tag{13}$$

Proof: Please refer to Appendix D. ■

We observe from Eq. (13) that the asymptotic critical DeNS depends on the product of the node density λ and the InF γ. In the SeWN having a sufficiently high node density of λ ($\lambda \to \infty$) and a sufficiently low positive InF γ ($\gamma \to 0$), the asymptotic critical DeNS can be used as the criterion of determining the effect of node-selfishness on the network's connectivity. If we have $S < S^*(\lambda, \gamma)$, the SeWN $\mathcal{G}(\lambda, \gamma, S)$ is connected with a specific probability; otherwise, it is unconnected.

In the SeWN, which is free from mutual interference ($\gamma = 0$), the following theorem related to the critical DeNS holds.

Theorem 4 (Asymptotic Critical DeNS for $\gamma = 0$): For the node density obeying $\lambda \to \infty$, the critical DeNS has the following asymptotic behavior

$$S^*(\lambda) = 1 - \Theta\left(\frac{1}{\psi(\lambda)}\right). \tag{14}$$

Proof: Please refer to Appendix E. ■

From Eq. (14), the critical DeNS increases and tends to a certain asymptotically near-constant value, as the node density increases. Meanwhile, the probability of attaining connectivity for the SeWN increases, as the critical DeNS increases.

Based on the asymptotic DeNS S^* defined in *Theorem 3* and *Theorem 4*, we characterize the network connectivity of the SeWN $\mathcal{G}(\lambda, \gamma, S)$ by comparing the SeNs' DeNS S to the asymptotic critical DeNS S^*. If we have $S < S^*$, this SeWN is connected with a certain probability; otherwise, it is unconnected. Hence, the asymptotic critical DeNS is capable of characterizing the network's connectivity from a node-selfishness perspective. Furthermore, since both the SeN's available resources Υ and the received incentive Ξ affect its selfish/altruistic inclination, we also maintain the network connectivity of the SeWN, which consists of the SeNs having different amounts of available resources, by adjusting the incentives for stimulating these SeNs. In the following section, we provide an example for analyzing the relationship between the residual energy possessed by the SeNs and the connectivity of the SeWNs.

IV. CONNECTIVITY OF SeWN UNDER ENERGY-CONSCIOUS NODE-SELFISHNESS MODEL

In our SeWN, we assume that the SeNs have limited energy resources, but a sufficiently large number of long CDMA spreading codes, which implies that the mutual interference amongst the SeNs is negligible. Hence we have $\gamma = 0$. We refer to the specific nodes generating data packets as the sources and those finally receiving these data packets as the corresponding destinations. The shortest line-of-sight (LOS) distance between the source-destination pair is denoted by L_1, and the set of SeNs within the rectangular area ($L_1 \times L_2$) is denoted by $\mathcal{M}$ with a cardinality of $|\mathcal{M}| = \lambda L_1 L_2$. To deliver data packets from the sources to their corresponding destinations, the connectivity of such a SeWN has to be retained for guaranteeing that there

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exists a path consisting of several SeNs between the source-destination pair.

Again, the SeN's node-selfishness is characterized by both its energy resources Υ, i.e., its residual energy and the amount of its instantaneously consumed energy, and the incentive Ξ. In our SeWN scenario, the resource consumption of a packet's transmission for all SeNs is assumed to be identical. Therefore, the effect of the instantaneously consumed resources on the node-selfishness is also approximately equal. For simplicity, in this contribution, we pay more attention to the dissecting of the residual energy resource associated with the node-selfishness, given the globally known effects of the instantaneously consumed resources. Additionally, a price-based incentive mechanism [7] is employed by the sources for stimulating the specific SeNs only having a small residual energy to connect with their neighbor nodes in the interest of sustaining connectivity. In this mechanism, the source pays an energy price β in exchange for the SeN's residual energy resource. The energy price β increases, as the amount of the SeN's residual energy decreases. In the following subsections, we propose an energy-conscious node-selfishness model for characterizing the effects of both the SeN's residual energy E and the received energy price β on its DeNS, and consequently also on the connectivity of this SeWN. In our regime, the SeNs of different residual energy are paid to avoid increasing their DeNS in the interest of retaining the network's connectivity, as formulated in *Theorem 4*.

A. ENERGY-CONSCIOUS NODE-SELFISHNESS MODEL

In this subsection, we formulate the relationship between the SeN's DeNS and its residual energy. The DeNS increases as the residual energy retained at the SeN is depleted. Typically, when an SeN has a high residual-energy level, it is likely to be more willing to forward packets received from its neighbor nodes, while in the presence of mediocre residual-energy level, the willingness of forwarding packets reduces. Finally, in the presence of a low residual-energy level, the SeN may refuse to forward packets all together. By mapping the residual energy to the DeNS (c.f. the hyperbolic selfishness behavior in [27]), we arrive at the plausible energy-conscious node-selfishness model of

$$S(E, \beta) = 1 - \left(\frac{1 - e^{-\beta E}}{1 - e^{-\bar{E}}} \right)^{\alpha}, \tag{15}$$

where E is the residual energy amount, $\bar{E}$ is the amount of the total energy initially possessed by the SeN, α and β are the individual characteristics of the SeN and the energy price. When $\alpha = 1$, the SeN does not have any prejudice against dissipating its energy resources; when $\alpha < 1$, the SeN has an altruistic inclination concerning its energy dissipation; while for $\alpha > 1$, the node has a selfish inclination, hence aiming for conserving energy. In a price-based incentive mechanism, the SeN's willingness of forwarding packets is affected by the energy price paid by other nodes. The SeN's willingness of forwarding packets increases as the energy price increases, thus leading to that its DeNS decreases. Let us briefly consider two extreme cases: for $E = 0$, the DeNS $S = 1$, which means that no SeNs are willing to forward packets; by contrast, for $E = \bar{E}$, the DeNS $S = 0$, which means that the SeNs are altruistically willing to forward packets. Naturally, it is more common that we have $0 < E < \bar{E}$, yielding $0 < S < 1$, which is also affected by the energy price β.

B. IMPACT OF RESIDUAL ENERGY ON NETWORK CONNECTIVITY

Recall that *Theorem* 4 illustrates the relationship between the critical DeNS and the network connectivity in the case of ignoring the nodes' mutual interference, while the energy-conscious node-selfishness model characterizes the relationship between the SeN's DeNS and its residual energy. Hence, both *Theorem* 4 and the energy-conscious node-selfishness model are exploited here for evaluating the impact of residual energy on the network connectivity, whilst ignoring the nodes' mutual interference. We define the *critical amount of residual energy* E^* as a threshold value for determining whether the SeWN is connected with a specific probability or not. If the residual energy E possessed by the SeN is higher than the critical amount of residual energy E^*, the SeWN maintains the network connectivity with a certain probability; otherwise, the SeWN is unconnected.

Theorem 5 (Critical Amount of Residual Energy): By using *Theorem 4*, the critical amount of residual energy for the SeN required for maintaining the network connectivity with a certain probability is expressed as

$$E^*(\lambda, \beta) = -\frac{1}{\beta} \ln \left(1 - \eta \sqrt[\alpha]{\frac{c_6}{\psi(\lambda)}} \right), \tag{16}$$

which is a monotonically decreasing function of node density λ and β, and where $\eta = 1 - \exp(-\bar{E})$ and c_6 is a constant related to P, N_0 and ζ.

Proof: Please refer to Appendix F. ∎

To guarantee the connectivity of the SeWN with a certain probability, the source evaluates the critical amount of residual energy as a function of λ, α and β. We stipulate the idealized simplifying assumption that this information may be inferred by learning techniques from the surrounding environment. The critical amount of residual energy E^* is a monotonically decreasing function of β, as seen from *Theorem 5*. Accordingly, the source may pay a commensurately increased energy price β to decrease the corresponding critical amount of residual energy E^* of each and every SeN for the sake of maintaining the network's connectivity formulated as $E^* \leq E$. Nevertheless, for the sake of minimizing the energy price, the source also decreases its critical amount of residual energy E^* to its residual energy E, thus arriving at the optimal condition of $E^* = E$. Therefore, in the SeWNs, where all SeNs have different amounts of residual energy, the critical amount of residual energy E^* in *Theorem* 5 is used for the sake of satisfying the network's connectivity.

V. SIMULATION RESULTS

In this section our simulation results are provided for characterizing the connectivity of the SeWN. We set the s-SINR threshold as $\zeta = 0$dB.

A. THE NETWORK CONNECTIVITY

Fig. 3, Fig. 4 and Fig. 5 show the topological examples of the connectivity of the SeWN in the simulation area having an edge-length of 40m and a node density of $\lambda = 0.5/\text{m}^2$. The central node is marked with "$\triangle$", and the SeNs are denoted by the marker "+", which are directly or indirectly connected to the central node. The points denoted by the marker "x" are unconnected to the central node either directly or indirectly.

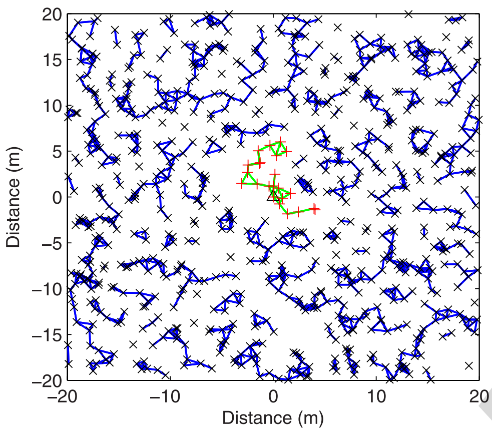

FIGURE 3. There are only LCCs of finite size in the simulation area having an edge-length of 40m with $\lambda = 0.5$, $\gamma = 0.08$ and $S = 0$.

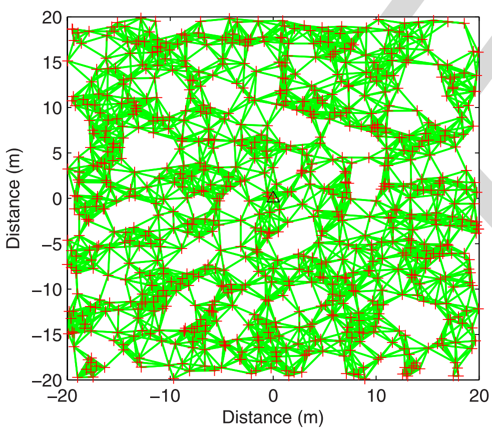

FIGURE 4. There exists an LCC spanning from one side to the other side of the simulation area having an edge-length of 40m with $\lambda = 0.5$, $\gamma = 0.008$ and $S = 0$.

Fig. 3 shows the topology of this SeWN for the InF $\gamma = 0.08$ and the DeNS $S = 0$. We readily observe that the central node is unable to connect to all nodes of the entire SeWN. Fig. 4 depicts a topology example of the SeWN for a reduced InF $\gamma = 0.008$ and the DeNS $S = 0$, where the central node is now readily capable of establishing connection with any of the nodes. As expected, given a fixed node density λ and a DeNS S, the probability of maintaining the connectivity of the SeWN reduces, as the InF increases.

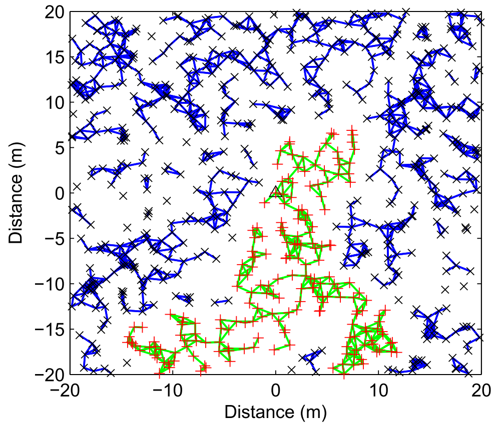

FIGURE 5. The central node cannot connect to all edge-nodes in the simulation area having an edge-length of 40m with $\lambda = 0.5$, $\gamma = 0.008$ and $S = 0.95$.

Fig. 5 illustrates a topology example of the SeWN for $\gamma = 0.008$ and $S = 0.95$, where the central node is unable to connect with all nodes of the entire SeWN. By observing the results of Fig. 4 and Fig. 5, we infer that the probability of maintaining the connectivity of the SeWN reduces, as the DeNS increases.

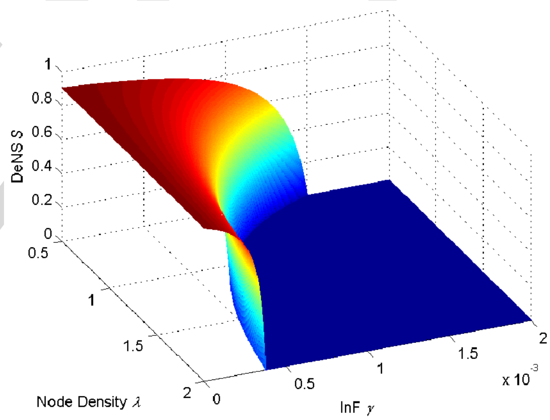

FIGURE 6. The upper bound of the critical DeNS for $\lambda = [0.5, 2]$ and $\gamma = [0, 0.002]$ evaluated from Eq. (11).

Fig. 6 and Fig. 7 show the lower and upper bounds of the critical DeNS, as evaluated from Eqs. (11) and (12) versus both the InF γ and the node density λ. Observe in these two figures that as $\lambda \to \infty$ and $\gamma \to 0$, the DeNS varies with the product of λ and γ. When the DeNS is $S = 0$ at the top of these surfaces, we observe that the InF γ decreases, as the node density λ increases. Furthermore, when the InF is $\gamma = 0$, the DeNS S increases and tends to a certain fixed value, as the node density obeys $\lambda \to \infty$. It becomes explicit from Fig. 6 and Fig. 7 that the upper bound of the critical DeNS is higher than its lower bound.

B. CONNECTIVITY OF SeWN VERSUS ENERGY RESOURCES

In practical networks, there are parallel source-destination pairs. Furthermore, some SeNs may be simultaneously used

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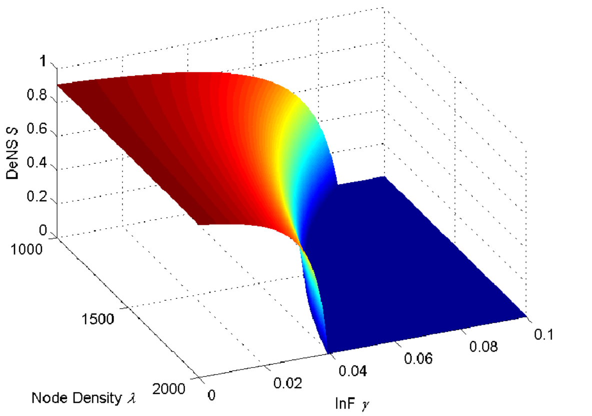

FIGURE 7. The lower bound of the critical DeNS for $\lambda = [1000, 2000]$ and $\gamma = [0, 0.1]$ evaluated from Eq. (12).

for assisting the packet transmissions of different source-destination pairs. Considering that an SeN is shared by several source-destination pairs and its residual energy is also known to these pairs, the energy price paid to this SeN by a certain source-destination pair is correlated with this specific SeN's residual energy, but it is independent of the actions of the other pairs. Equivalently, we may assume that the parallel source-destination pairs are independent of each other. This allows us to simplify the simulation scenario by considering only a single source-destination pair. Fig. 8 shows the SeWN topology with the SeN's DeNS $S = 0.5$ in the area of (40m×1m). The source and the destination are marked as "△" and "○", respectively. The points denoted by the marker "+" are the nodes, which are either directly or indirectly connected to the source, while the nodes denoted by the marker "x" are isolated from the source. The top subplot shows the SeWN topology for a node density of $\lambda = 1$, where the SeN is unable to connect to the destination. The bottom subplot shows the SeWN topology for a node density of $\lambda = 2$, where the source successfully transmits its packets to the destination. This implies that a higher node density results in a higher successful probability of packet delivery.

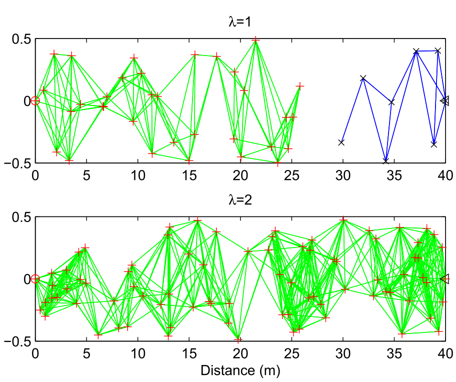

FIGURE 8. The SeWN topology for different node densities in the area of (40m×1m).

Fig. 9 shows the variation of the critical DeNS evaluated from Eq. (14) as well as its upper and lower bounds versus the node density. We employ the classic Monte Carlo method for determining the proportion of packets successfully transmitted from the source to the destination in the area of (40m×1m). By randomly generating 30 different network topologies, we evaluated both the upper and lower bounds of the critical DeNS. The lower bound of the DeNS is determined under the condition that all random network topologies remain connected, while the upper bound is determined under the condition that all random network topologies are unconnected. Observe from Fig. 9 that the theoretical value of the critical DeNS evaluated from Eq. (14) is between the upper bound and the lower bound generated by the Monte Carlo method. Furthermore, the theoretical value, the upper bound and the lower bound of the critical DeNS increase, as the node density increases. This implies that this theoretical result of the critical DeNS can be invoked for determining whether the SeWN is connected or not.

We further illustrate the effect of the SeN's residual energy on the network connectivity in the SeWN, while ignoring the nodes' mutual interference. Fig. 10 shows the variations of the critical amount of residual energy with the node density for different energy prices of $\beta = \{0.1, 0.5, 1\}$. Observe that

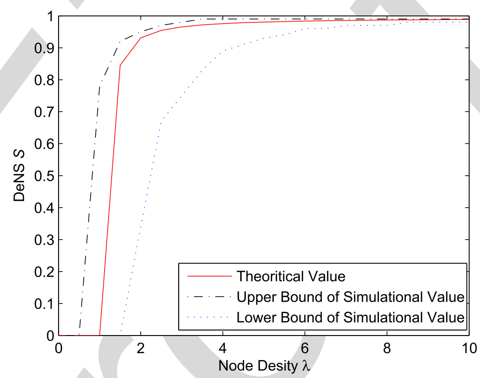

FIGURE 9. The critical DeNS versus node density as evaluated from Eq. (14).

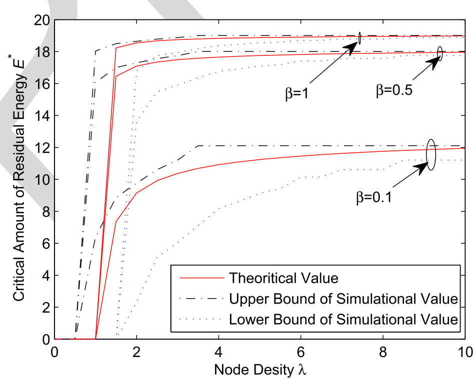

FIGURE 10. The critical amount of residual energy versus node density for different energy prices of $\beta = \{0.1, 0.5, 1\}$ as evaluated from Eq. (16) and by Monte Carlo simulations respectively.

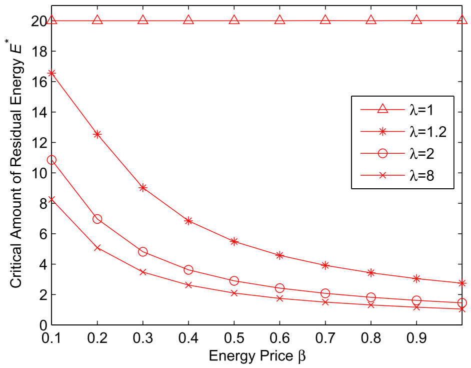

FIGURE 11. The critical amount of residual energy versus the energy price for node densities of $\lambda = \{1, 1.2, 2, 8\}$ as evaluated from Eq. (16) and by Monte Carlo simulations respectively.

the theoretical value of the critical amount of residual energy is between the upper bound and the lower bound generated by the Monte Carlo method, and the critical amount of residual energy decays to a certain constant value, as the node density increases for a specific energy price. Meanwhile, the theoretical value of the critical amount of residual energy evaluated from Eq. (16) decreases, as the energy price increases in the SeWN scenario associated with a certain node density λ. Fig. 11 depicts the critical amount of residual energy versus the energy price for $\lambda = \{1, 1.2, 2, 8\}$ as evaluated from Eq. (16). In an SeWN scenario associated with a certain node density, the critical amount of residual energy of transmitting the packets decreases, as the energy price increases. Thus, for the SeWN relying on SeNs possessing a low residual energy level, the source has to provide a sufficiently high energy price for maintaining the network connectivity. At a specific energy price paid by the source, the critical amount of residual energy decreases, as the node density increases.

VI. CONCLUSIONS

In this paper, we determined the impact of the node-selfishness on the network's connectivity and derived both the upper and lower bounds of the DeNS with the aid of percolation theory. Then the asymptotic critical DeNSs were obtained for SeWNs with the aid of these two bounds. Furthermore, we developed an energy-conscious node-selfishness model, which is a function of both its own residual energy and the energy price paid by the source. The critical amount of residual energy derived from the asymptotic critical DeNS was used for characterizing the network's connectivity from a residual-energy perspective. Therefore, both the asymptotic critical DeNS and the critical amount of residual energy were taken into account by our analysis of the network's connectivity.

APPENDIX A
PROOF OF PROPOSITION 1

In SeWNs, the interference level and the DeNS critically affect the network connectivity. The interference level directly impacts the quality of the received signal. Likewise, the DeNS degrades the probability of successfully forwarding packets and thus may destroy the link's connectivity all together. Since the InF and the DeNS are directly related to the relative user-load and the DeNS respectively, we may determine the critical surface

$$SF(\lambda, \gamma, S) = 0 \tag{17}$$

from an interference level and a node-selfishness perspective in the SeWN $\mathcal{G}(\lambda, \gamma, S)$, respectively. Considering the effect of the interference level on the connectivity of the SeWN, we define the critical InF as

$$\gamma = \gamma^*(\lambda, S), \tag{18}$$

given a specific node density λ and a DeNS S. Thus we have the parameter triplet $(\lambda, \gamma^*(\lambda, S), S)$, which separates the parameter space $\mathbb{S}(\lambda, \gamma, S)$ in two parts, corresponding to the connectivity resigon and the disconnectivity region, respectively. Similarly, when considering the effect of the node-selfishness on the connectivity of the SeWN, we define the critical DeNS as

$$S = S^*(\lambda, \gamma), \tag{19}$$

given a specific node density λ and a particular InF γ. Furthermore, we have the parameter triplet $(\lambda, \gamma, S^*(\lambda, \gamma))$, which also divides the parameter space $\mathbb{S}(\lambda, \gamma, S)$ in two parts: the connectivity region and the disconnectivity region. Therefore, determining the critical surface $SF(\lambda, \gamma, S)$ is equivalent to finding the critical InF $\gamma^*(\lambda, S)$ or to determining the critical DeNS $S^*(\lambda, \gamma)$ for maintaining the SeWN's connectivity with a specific probability.

APPENDIX B
PROOF OF THEOREM 1

In order to prove this theorem, we first prove the bond percolation of [14] on the square lattice, which is related to the SeWN, and then find the sufficient condition of the network connectivity based on the bond percolation.

The SeWN $\mathcal{G}(\lambda, \gamma, S)$ is mapped onto a square lattice $\mathcal{L}$ with edge length ρ over the plane, as depicted in Fig. 12.

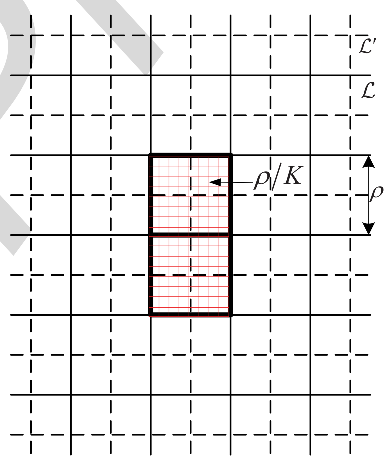

FIGURE 12. Lattice $\mathcal{L}$ with length ρ and its dual $\mathcal{L}'$ (dashed), and a square has some subsquares of area $\frac{\rho}{K} \times \frac{\rho}{K}$.

Let $\mathcal{L}'$ be the dual lattice of $\mathcal{L}$, which is created by placing a vertex in the center of every square of $\mathcal{L}$ and an edge across every edge of $\mathcal{L}$. Let us now consider the PPP of the node density λ over the plane, where each square of the original lattice $\mathcal{L}$ contains on average $\lambda\rho^2$ SeNs. The parameter K is related to the node density λ and we set it to a value satisfying the condition of $\| x \| \leq \frac{\sqrt{5}\rho}{K} \leq \delta$, where $\| x \|$ is the average distance between two adjacent SeNs. In the original lattice $\mathcal{L}$, each square is again divided into K^2 subsquares of size $\frac{\rho}{K} \times \frac{\rho}{K}$. A square of $\mathcal{L}$ is said to be *populated* [20], if all its subsquares contain at least one SeN. An edge of the original lattice $\mathcal{L}$ is said to be open, if the following conditions are satisfied: 1) both squares adjacent to this edge are populated; 2) the total number of SeNs located in the two squares adjacent to this edge as well as all their direct neighboring squares (that is, all the squares having at least one vertex in common with these two squares) is less than or equal to $(N+1)$, where the integer parameter N is defined as

$$N = \inf_{\text{s.t. } \|x\| \leq \frac{\sqrt{5}\rho}{K}} \left\lfloor \frac{1}{\gamma(1-S)M} \left(\frac{(1-S)l(\| x \|)}{\zeta} - \frac{N_0}{P} \right) \right\rfloor, \tag{20}$$

with $\lfloor \cdot \rfloor$ being the integer floor operator. Eq. (20) puts a limit to the interference contribution. An edge of the dual lattice $\mathcal{L}'$ is said to be *open* (resp. *closed*) if and only if the corresponding edge of $\mathcal{L}$ is open (resp. closed). A path (in $\mathcal{L}$ or $\mathcal{L}'$) is said to be *open* (resp. *closed*), if all edges forming this path are open (resp. closed).

Based on the above definitions, we now prove the bond percolation on the dual lattice $\mathcal{L}'$. The number of the SeN in a subsquare and a square is denoted by X and Y, which are two independent Poisson random variables of the parameters $\lambda(\frac{\rho}{K})^2$ and $10\lambda\rho^2$, respectively. In the dual lattice $\mathcal{L}'$, the event of an arbitrary open edge happens to include the following events: the first event is that $1 \leq X \leq \frac{N}{12K^2}$, while the second event is that $Y \leq \frac{5N}{6}$. Therefore, in $\mathcal{L}'$ the probability of an arbitrary open edge obeys

$$1 - S = \mathbb{P}^{2K^2}\left(1 \leq X \leq \frac{N}{12K^2}\right)\mathbb{P}\left(Y \leq \frac{5N}{6}\right). \tag{21}$$

Since both X and Y are independent Poisson random variables of the parameters $\lambda(\frac{\rho}{K})^2$ and $10\lambda\rho^2$, respectively, by invoking the Chebyshev's inequality [28] we arrive at

$$\lim_{\lambda\to\infty} \mathbb{P}^{2K^2}\left(1 \leq X \leq \frac{\lambda\rho^2(1+\varepsilon)}{K^2}\right)\mathbb{P}\left(Y \leq 10\lambda\rho^2(1+\varepsilon)\right) = 1. \tag{22}$$

For the sake of combining of IEq. (21) and Eq. (22), we have to set the number of SeNs $N = \lfloor 12\lambda\rho^2(1+\varepsilon) \rfloor$. Based on this number together with Eq. (20), we obtain the DeNS $S = S^l(\lambda, \gamma)$, where we have

$$S^l(\lambda, \gamma) = 1 - \frac{\zeta N_0}{P\psi(\lambda) - 12\lambda\zeta\gamma PM\rho^2(1+\varepsilon)} \tag{23}$$

for $\varepsilon > 0$ and $\gamma \leq \frac{1}{12M\lambda\rho^2(1+\varepsilon)}\left(\frac{\psi(\lambda)}{\zeta} - \frac{N_0}{P}\right)$, with $\psi(\lambda) = l\left(\sqrt{5}\rho/K\right)$ being a monotonically increasing function of the node density λ, such that $\lim_{\lambda\to\infty} \psi(\lambda) = M$. Thus, it may be readily seen from IEq. (21) and Eq. (22), that the probability of an arbitrary edge being open is $\lim_{\lambda\to\infty} S = 0$. With the aid of [20, Lemma 3 and Th. 3], we can also state that there a.s. exists an open path of infinite size in $\mathcal{L}'$ for λ tending to infinity, while $\gamma \leq \frac{1}{12M\lambda\rho^2(1+\varepsilon)}\left(\frac{\psi(\lambda)}{\zeta} - \frac{N_0}{P}\right)$ and $S \leq S^l(\lambda, \gamma)$.

We still have to show that there exists an LCC of infinite size, namely $\mathcal{P}(\lambda, \gamma, S) = 1$, in the SeWN $\mathcal{G}(\lambda, \gamma, S)$ with λ tending to infinity, while $\gamma \leq \frac{1}{12M\lambda\rho^2(1+\varepsilon)}\left(\frac{\psi(\lambda)}{\zeta} - \frac{N_0}{P}\right)$ and $S \leq S^l(\lambda, \gamma)$. In two adjacent subsquares of the edge length ρ/K, the distance between any two SeNs is at most $\sqrt{5}\rho/K$. Since $\sum_{k\neq i,j} p_k l(\| x_k - x_i \|) \leq NMP$ from Eq. (2) and IEq. (3), the s-SINR received by the SeN in a subsquare is

$$\frac{p_i l(\| x_j - x_i \|)(1-S)}{N_0 + \gamma \sum\limits_{k\neq i,j} p_k l(\| x_k - x_i \|)(1-S)} \geq \zeta. \tag{24}$$

Each SeN in a given subsquare is connected to all the SeNs in the adjacent subsquares, and the SeNs in all subsquares of a certain square belong to the same LCC. If there exists an open path of infinite size in $\mathcal{L}'$, there exists an LCC of infinite size in the SeWN $\mathcal{G}(\lambda, \gamma, S)$. Therefore, we proved that there exists an infinite-size LCC in the SeWN $\mathcal{G}(\lambda, \gamma, S)$, as λ tends to infinity, while $\gamma \leq \frac{1}{12M\lambda\rho^2(1+\varepsilon)}\left(\frac{\psi(\lambda)}{\zeta} - \frac{N_0}{P}\right)$ and $S \leq S^l(\lambda, \gamma)$.

APPENDIX C
PROOF OF THEOREM 2

In order to prove this theorem, we first prove the site percolation [14] on the square lattice, which is related to the SeWN, and then find the necessary condition of the network connectivity based on this site percolation.

The SeWN $\mathcal{G}(\lambda, \gamma, S)$ is similarly mapped onto a new square lattice $\mathcal{L}''$ over the plane as the lattice $\mathcal{L}$ mentioned in the proof of *Theorem 1*, except for the difference that it was an edge length of $\delta/2$, when considering an arbitrary node in $\mathcal{G}(\lambda, \gamma, S)$ as the origin of the square of $\mathcal{L}''$. With the aid of Eq. (3), we arrive at $\sum_{k\neq i,j} p_k l(\| x_k - x_i \|) \geq \zeta N' N_0 - 2PM$, where N' is the number of the SeNs in a square. We thus have the following result

$$\frac{p_j l\left(\| x_j - x_i \|\right)(1-S)}{N_0 + \gamma \sum\limits_{k\neq i,j} p_k l\left(\|x_k - x_i\|\right)(1-S)} \leq \frac{PM(1-S)}{N_0 + \gamma(\zeta N' N_0 - 2PM)(1-S)}. \tag{25}$$

If the right-hand side of the above inequality is clearly smaller than ζ, node i is unable to communicate with any other nodes in this square. If the number of SeNs is

$$N' \geq \frac{(1-S)PM(1+2\zeta\gamma) - N_0\zeta}{(1-S)\gamma N_0 \zeta^2}, \tag{26}$$

all SeNs in this square are isolated. Using the site percolation theory [14], we declare a square of $\mathcal{L}''$ open, if this square contains at most $2\frac{(1-S)PM(1+2\zeta\gamma)-N_0\zeta}{(1-S)\gamma N_0\zeta^2}$ SeNs; otherwise, the square of $\mathcal{L}''$ is declared closed. Note that the number of SeNs inside a square is a Poisson random variable of the parameter $\lambda\delta^2/4$. If we have

$$\lim_{\lambda\to\infty}\mathbb{P}\left(2\frac{(1-S)PM(1+2\zeta\gamma)-N_0\zeta}{(1-S)\gamma N_0\zeta^2}\le\frac{(1-\varepsilon)\lambda\delta^2}{4}\right)=0, \tag{27}$$

which is obtained with the aid of the Chebyshev's inequality [28], we can obtain that $\lim_{\lambda\to\infty}\mathbb{P}(\text{a square is open})=0$ and hence $\lim_{\lambda\to\infty}\mathbb{P}(\text{a square is closed})=1$. This means that the origin is a.s. surrounded by a closed circuit (that consists of some closed squares in $\mathcal{L}''$). From Eq. (27), we can obtain the DeNS of

$$S^u(\lambda,\gamma)=1-\frac{8N_0\zeta}{8PM(1+2\zeta\gamma)-(1-\varepsilon)\lambda\gamma N_0\zeta^2\delta^2}, \tag{28}$$

for $\lambda>\frac{16PM}{\varepsilon N_0\zeta\delta^2}$ and $\gamma\le\frac{8PM}{(1-2\varepsilon)\zeta^2\lambda\delta^2N_0}$.

For $\lambda>\frac{16PM}{\varepsilon N_0\beta\delta^2}$, $\gamma\le\frac{8PM}{(1-2\varepsilon)\zeta^2\lambda\delta^2N_0}$ and $S\ge S^u(\lambda,\gamma)$, we have proved that the origin is surrounded by a closed circuit in $\mathcal{L}''$, but we still have to prove that there is no infinite-size LCC in the SeWN $\mathcal{G}(\lambda,\gamma,S)$. Let us consider the pair of nodes i and j, such that node i is located inside an open square surrounded by a closed circuit, while node j is located inside another open square, but on the other side of the previous circuit. As these two SeNs are separated by the circuit, the distance $\| x_i-x_j \|$ between them is larger than $\frac{\delta}{2}$. For $\frac{\delta}{2}<\| x_i-x_j \|<\delta$, the s-SINR observed at node i upon receiving from node j becomes

$$s\text{-SINR}_{ji}\le\frac{PM(1-S)}{N_0+\gamma(1-S)(\zeta N'N_0-2PM)}. \tag{29}$$

Substituting IEq. (26) into the above inequality, we find that $s\text{-SINR}_{ji}\le\zeta$, which means that there is no connected bidirectional link between node i and node j. Furthermore, for $\delta>\| x_i-x_j \|$, we obtain

$$s\text{-SINR}_{ji}\le\frac{Pl(\| x_i-x_j \|)(1-S)}{N_0+\gamma(1-S)(\zeta N'N_0-2PM)}. \tag{30}$$

Likewise, we still have $s\text{-SINR}_{ji}\le\zeta$, which implies the absence of the connected bidirectional link between node i and node j. Consequently, this origin belongs to a finite-size LCC. Because the origin is arbitrary, we only have some finite-size LCCs in the SeWN. Therefore, we have proved that there only exist some finite-size LCCs in $\mathcal{G}(\lambda,\gamma,S)$, namely $\mathcal{P}(\lambda,\gamma,S)=0$, for $\lambda>\frac{16PM}{\varepsilon N_0\beta\delta^2}$, $\gamma\le\frac{8PM}{(1-2\varepsilon)\zeta^2\lambda\delta^2N_0}$ and $S\ge S^u(\lambda,\gamma)$.

APPENDIX D
PROOF OF THEOREM 3

From Eqs. (11) and (12), $S^l(\lambda,\gamma)$ and $S^u(\lambda,\gamma)$ are expressed as $S^l(\lambda,\gamma)\triangleq\frac{1}{c_1\psi(\lambda)-c_2\lambda\gamma}$ and $S^u(\lambda,\gamma)\triangleq\frac{1}{c_3+c_4\gamma-c_5\lambda\gamma}$ respectively, where c_1, c_2, c_3, c_4 and c_5 are corresponding constants. As the node density obeys $\lambda\to\infty$ and the InF obeys $\gamma\to 0$, both $c_1\psi(\lambda)$ and $c_3+c_4\gamma$ tend to $\frac{PM}{N_0\zeta}$. Then we can find a pair of constants ν and υ, so that $\lim_{\lambda\to\infty,\gamma\to 0}P(c_2\lambda\gamma\le\nu c_5\lambda\gamma)=1$ and $\lim_{\lambda\to\infty,\gamma\to 0}P(c_5\lambda\gamma\le\upsilon c_2\lambda\gamma)=1$. Thus, we have a unified asymptotic expression of $\Theta(\lambda\gamma)$ for both $c_2\lambda\gamma$ and $c_5\lambda\gamma$, as the node density $\lambda\to\infty$ and the InF $\gamma\to 0$. Now, this theorem has been proven.

APPENDIX E
PROOF OF THEOREM 4

In the SeWN which is free from mutual interference ($\gamma=0$), the lower bound of the DeNS is $S^l(\lambda,0)=\frac{\zeta N_0}{P\psi(\lambda)}$, while its upper bound is $S^u(\lambda,0)=\frac{\zeta N_0}{PM}$. There exists a pair of constants ν' and υ' so that we have $\lim_{\lambda\to\infty}P(S^l(\lambda,0)\le\nu'\kappa^l(\lambda,0))=1$ and $\lim_{\lambda\to\infty}P(S^u(\lambda,0)\le\upsilon'\kappa^u(\lambda,0))=1$. Based on this point together with $\lim_{\lambda\to\infty}\psi(\lambda)=M$, we have a unified expression $\Theta\left(1/\psi(\lambda)\right)$ for both $S^l(\lambda,0)$ and $S^u(\lambda,0)$, as the node density obeys $\lambda\to\infty$. Hence this theorem has been proven.

APPENDIX F
PROOF OF THEOREM 5

If the DeNS of a specific node is known, its residual energy is evaluated from Eq. (15). By finding the inverse function of Eq. (15), we arrive at

$$E=-\ln(1-\eta\sqrt[\alpha]{1-S})/\beta, \tag{31}$$

which is a monotonically decreasing function of the DeNS S, because Eq. (15) is a monotonically decreasing function of the residual energy E. *Theorem 4* formulates the condition of the network connectivity in terms of the DeNS as

$$S=1-c_6/\psi(\lambda), \tag{32}$$

which indicates that a sufficiently high node density λ is required for maintaining the network connectivity. Hence, the critical amount of residual energy of the SeN is expressed as $E^*(\lambda,\beta)=-\ln(1-\eta\sqrt[\alpha]{c_6/\psi(\lambda)})/\beta$ with the aid of Eqs. (31) and (32).

Furthermore, bearing in mind that Eq. (31) is a monotonically decreasing function of the DeNS S and that the function $S=1-\frac{c_6}{\psi(\lambda)}$ is a monotonically increasing function of λ, the critical amount of residual energy $E^*(\lambda,\beta)$ is a monotonically decreasing function of λ.

Additionally, setting the derivative of Eq. (31) with respect to β yields

$$\frac{\partial E^*(\lambda,\beta)}{\partial\beta}=\frac{\ln\left(1-\eta\sqrt[\alpha]{c_6/\psi(\lambda)}\right)}{\beta^2},$$

for $0<\eta<1$ and $0<\frac{c_6}{\psi(\lambda)}<1$. We can now verify that $\frac{\partial E^*(\lambda,\beta)}{\partial\beta}<0$. Since we have $\frac{\partial E^*(\lambda,\beta)}{\partial\beta}<0$, the critical amount of residual energy is a monotonically decreasing function of β. This completes the proof.

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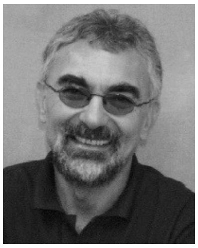

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