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A Channel Hopping Algorithm for Guaranteed Rendezvous in Cognitive Radio Ad Hoc Networks Using Swarm Intelligence

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Abstract Achieving fast Time to Rendezvous (TTR) on a common coordination channel in an Ad hoc network remains a contemporary issue in Cognitive Radio research. In this paper, we present a new channel hopping algorithm for the selection of control channel in a heterogeneous, spatial, and time varying spectrum environment, with no pre-existing infrastructure such as an access point or a base station. We adopt the use of the bio-mimicry concept to develop a swarm intelligence based mechanism, which will guide nodes to hop unto the most prominent channel while waiting for potential neighbourhood discovery. A closed form expression for the TTR and Expected TTR (ETTR) was derived for various network scenarios. We provide a theoretical analysis of the TTR and ETTR of our algorithm, and show that our algorithm provides a TTR within order *O(M)* when compared with Generated Orthogonal Sequence and Channel Rendezvous Sequence of order $O(P^2)$. The algorithm further provides an improved performance in comparison to the Jump–Stay and Enhanced Jump–Stay Rendezvous Algorithms.

Keywords Cognitive radio · Ad hoc network · CRAHN · Rendezvous · TTR · ETTR

1 Introduction

The need to deploy decentralized Cognitive Radio (CR) based Ad hoc networks is receiving recent attention owing to its possible application in emergency and military inclined operations. CR refers to a radio capable of identifying its spectral environment and able to optimally adjust its transmission parameters to achieve an interference-free

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communication channel [1]. While most works on CR have focused on infrastructure based networks, little has been done thus far with respect to the Ad hoc based option [2]. This might be attributed to certain existing problems that are closely related to the heterogeneous nature of the spectrum environment (including spatial and time variations), co-tier and cross-tier interference and the overtly large spectrum space to be searched for channel convergence in an Ad hoc setup [3]. Consequently, our research is motivated by the need to improve on the time to converge on a common coordination channel for CR nodes involved in an Ad hoc network. In Cognitive Radio Ad Hoc Networks (CRAHN), nodes seeking to communicate must first converge on a common channel to establish a link. This coordination or control channel selection process could be dedicated or dynamic [3] in nature. Dynamic control channel selection techniques have only just gained significant attention in literature owing to their flexibility in the wake of recent spectrum scarcity challenges. This motivates our aim to develop an improved dynamic control channel selection technique for CRAHN based operation. Two key performance metrics used for evaluating these dynamic techniques is the Time to Rendezvous TTR and the Expected TTR (ETTR). By rendezvous, reference is made to the process of converging on a common channel, which occurs when a Secondary User (SU) seeks to establish a communication link with another SU. Consequently, in this paper, we present a new dynamic control channel selection algorithm based on swarm intelligence, which provides an efficient hopping mechanism for convergence on the most prominent channel while CR nodes wait for potential neighbourhood discovery. To the best of our knowledge, the concept of swarm intelligence in the selection of control channel in CRAHN has not been applied. Hence, we seek to establish its use and advantages over some known techniques in CRAHN. Furthermore, we develop a closed form expression for the TTR and ETTR for various network scenarios, and provide a theoretical analysis of our algorithm's TTR.

2 Related Works

The concept of node convergence on a common channel in CR networks has gained tremendous attention in recent years. Channel hopping (CH) is one such technique where communicating CR nodes hop across different available spectrum. Horine and Turgut [4] developed an algorithm for initial network connection, whereby nodes seeking to join the network randomly visit potential channels while emitting attention signals (side tone) of length equivalent to a single Fast Fourier Transform (FFT) frame. They demonstrated that a short duration narrow bandwidth with low power attention signal can be detected in a high noise environment. However, we note from their analysis that the process of rendezvous is not bounded in time and consists of several points of failure. DaSilva and Guerreiro [5] used predefined non-orthogonal sequence to determine the order for visiting potential channels towards achieving rendezvous. The predefined sequence involved a random permutation of N available channels, though no preference for rendezvous on best channel was obtained for its TTR. Theis et al. [6] applied prime number modulo operation in addressing the blind rendezvous problem. They developed Modular Clock Algorithm (MCA) and a Modified MCA to address the weakness of MCA. MCA and MMCA showed considerable speed up in TTR, however rendezvous was not bounded in time for all scenarios. In [7], Liu et al. developed a robust Jump-Stay rendezvous algorithm that generates CH sequence in rounds for different CR nodes such that each round consists of two jump patterns; which is a random permutation of the M available channel and a stay pattern on any channel. They showed some improvements in TTR. Similar techniques were observed in [8–10] with some modifications and improvements over [7]. In [11], CR nodes are made to hop on available channels with varying velocity such that rendezvous can be achieved by different CRs whereas in [12], CH scheme were generated in clockwise and counter clockwise orientation to achieve rendezvous. Another approach to solve the rendezvous problem is the use of quorum-based systems used in [13–17]. In these works, cyclic quorum systems were designed based on difference sets. Despite varying unique contributions, we note some gaps in the existing design and take further steps in addressing these.

3 System Model

We consider a system model of a two-tier network as shown in Fig. 1 comprise primary base stations and a dense collection of SUs. All SUs are assumed to have closed access and share the same frequency with the PUs in an overlay spectrum sharing architecture. The PUs are considered holders of m channels uniquely indexed as $0, 1, 2, (m-1)$. The network comprises n SU nodes, such that $n \geq 2$ nodes share the network with PU in an overlay spectrum sharing mode. For simplicity, we consider the channels to be m non-overlapping orthogonal channels so that each channel has a bandwidth of $B_0 = B/m$. We consider the channel model to be subject to large scale fading and Rayleigh fading.

Therefore, the received Signal-to-Interference Noise Ratio (SINR) $\gamma_{m,n}$ for user n occupying channel m is given as

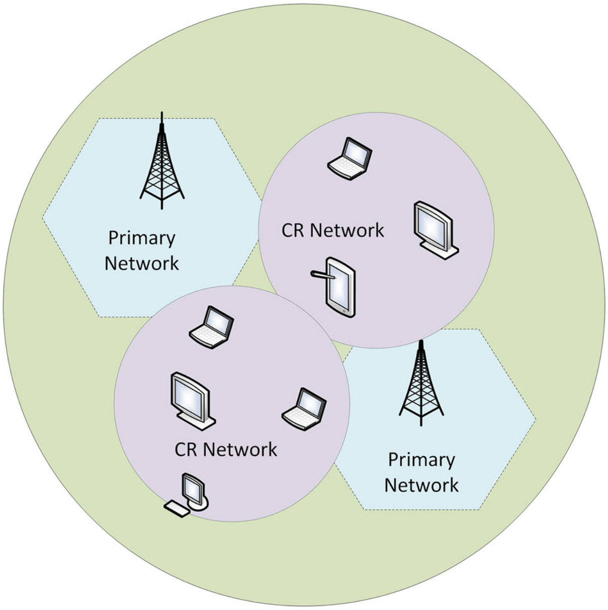


Fig. 1 System network model

$$\gamma_{m,n} = \frac{P^{s}_{m,n} * g^{s}_{m,n}}{\sum_{n\prime=1}^{n}\left(P^{s\prime}_{m,n\prime} * g^{s\prime}_{m,n\prime}\right) + P_{m,p} * g_{m,p} + N_0 * B_0} \tag{1}$$

where $P_{m,p}$ is the transmission power of PBS on channel m, $P^{s}_{m,n}$, and $P^{s\prime}_{m,n\prime}$ are the transmitting powers of the serving SU on channel m and the interfering nodes $n\prime$ respectively. $g^{s}_{m,n}$, $g^{s\prime}_{m,n\prime}$ and $g^{p}_{m,n}$ are the channel gains for the serving SU n, interference SUs $n\prime$ and the PBS on channel m. Based on Shannon's channel capacity theorem, we define $r_{m,n}$, such that each channel has capacity given as

$$r_{m,n} = B_0 * log_2(1 + \alpha * \gamma_{m,n}) \tag{2}$$

where α is is a constant SINR gap of AWGN channel to meet the target bit error rate and is defined as $\alpha = -1.5/ln(5BER)$.

The idea is to deposit pheromone trail that is proportional to $\gamma_{m,n}$ and rank channels accordingly. Consequently, the probability that node n will establish channel m as the most highly ranked channel and thus constitute the stay channel will be

$$Pr_{m,n} = \frac{\tau^{\alpha}_{m,n} * \eta^{\beta}_{m,n}}{\sum_{i=0}^{m}\tau^{\alpha}_{i,n} * \eta^{\beta}_{i,n}} \tag{3}$$

where $\tau_{m,n}$ and $\eta_{m,n}$ respectively denote the pheromone trail and the heuristic information for CR node n on channel m. Parameters α and β define the relative importance of the pheromone trail versus heuristic information. The heuristic value is defined as

$$\eta_{m,n} = \frac{r_{m,n}}{\sum_{i=0}^{m} r_{i,n}} \tag{4}$$

In general, CR nodes like the ant analogy are more likely to choose channels that have larger pheromone deposits and heuristic values. When each node receives a beacon message, the local pheromone concentration is updated as

$$\tau_{m,n} = (1-\rho)\tau_{m,n} + \rho\Delta\tau_{m,n} \tag{5}$$

where ρ is a variable $(0 < \rho < 1)$ that controls the evaporation rate of local pheromone deposits and which enables the system to eliminate channel m that is a bad solution, with high spectral activity or PU presence. $\Delta\tau_{m,n}$ denotes the pheromone trait deposited on channel m of node n, and is given as

$$\Delta\tau_{m,n} = Q/C_{m,n} \tag{6}$$

$$C_{m,n} = f(\gamma_{m,n}) \tag{7}$$

where $C_{m,n}$ is the cost of using channel m as the stay pattern by node n. Q is a positive coefficient of $C_{m,n}$, and the pheromone concentration will be accelerated if Q is bigger. Pheromone evaporation and reinforcement are carried out on the CR nodes which make the process of hopping on the best channel more efficient.

3.1 Problem Formulation

The use of Ant Colony Algorithm (ACA) methods for coordination and organization of network parameters has been observed in [18]. By drawing similarities, the use of such technique in achieving the goal of coordination among CR Ad Hoc Networks (CRAHN) nodes has been proposed in [19]. Let $A_{i,j}$ be sets of available channels observed by n nodes such that $i \in m$ and $j \in n$ and it holds true that at least a common channel exists, that is, $\cap A_{i,j} \neq \emptyset$ then A system rendezvous occurs if all n nodes seeking to communicate converge on one of the common channels $i \in m$. TTR and ETTR are the two important metrics to evaluate the system's performance. This work assumes time slotted frequency hopping transmission with fixed transmission time slots. We define notation T as the minimum time period taken to exchange control information between SUs. The IEEE defines T as 10 ms [20]. We note that scenarios are asynchronous and, therefore, we set time as $2T$ to ensure that complete beacon exchange occurs for overlapping hopping sequences. Our proposed ACA method deposits pheromone trails on the nodes of quality paths to reinforce the most promising channel in the channel hopping sequence.

3.2 Algorithm Development

We develop a novel channel hopping sequence generator called Swarm Aided Stay-Jump (SASJ) CH sequence. Our algorithm presents an original concept on how white spaces between PU transmissions should be visited by CR nodes in order to achieve rendezvous. Each round consists of a stay-pattern and a jump-pattern. To further describe our algorithm we need to define three key integers. If M is the number of available channels, r is defined as the step length, usually an integer in [1, M]. For simplicity we chose 1 as the step length, as channels will be visited sequentially on the ranked table. Here, i is the starting index and lies in the set $[0,(M-1)]$. The jump pattern J, lasts $2M$ time slots and the stay pattern S, lasts M time slots. In the stay pattern, the CR stays on the highest ranked channel index i and in the jump pattern the user starts on channel index i and keeps hopping in $[0, M-1]$ with step length r while performing the modulo operation around M. Similar works [5, 7, 8] in literature utilized prime number P modulo arithmetic to guarantee TTR under different rendezvous models. However, since P is the lowest prime number greater than or equal to P there will always be gaps between M and P thus resulting in increased TTR [5]. Here we simply adopt a wrap-around-M modulo arithmetic provided we show in theorem 4.1 that the set of indices R generated by the operation X mod M is a member set of $[0, M-1]$, where X is any positive integer , that is, $R = X \bmod M \subseteq [0, M-1]$

The pseudo code of SASJ is presented below:

1. Input: M, i, r, X, T
2. ACA parameters initialization: initial value of pheromone on each channel on node n and heuristic information is set
3. Rank channels according to their pheromone traits
4. Output SASJ hopping sequence for radio n, S_n
5. Set clock $t_T = TTR$
6. For $t_T > 4M$ do % remapping of time sequence for S
7. $t = t_T mod 4M$
8. For t =*0 to M-1* do
9. $S_{nS}(t) = i$ % wait mode
10. End For

```
For t=M to 3M-1 do
S_nJ(t) = (i + r * t) mod M % hop mode
End for
Rendezvous?
Return S and update ranking table
Else For t=3M to 4M do
S_2R(t) = (Z_th − (M − 1) + r * t) mod M
Return S and update ranking table
```

3.3 Simple Illustration

Assuming we have $M = 4$ channels. Then each channel is uniquely indexed [0, 3], the modulo operation is performed as i mod M, where i is the slot index .We consider a CRN consisting of user $n = 2$ for illustration purpose. We can show that without the need of time synchronization, rendezvous is bounded in time for our SASJ CH generator. Figure 2 shows two users, with different starting times to seek for potential neighbour performing the SASJ CH sequence with similar channel ranking, in this simple case we see that rendezvous occurs on channel index 0. With our SASJ, users can achieve rendezvous under various scenarios to be considered.

4 System Theorems

4.1 Theorem 1

Given any number sequence $X = n + 1$, such that $X, n \in \mathbb{Z}$, then the set of numbers R generated by the modulo operation X mod M, are permutations of positive integers whose values lie in the set [0, M − 1]. That is, $R = X \bmod M$,so that $R \in [0, M - 1], M \neq 0$.

4.2 Theorem 2

Under the symmetric model, any two radios performing SASJ achieve rendezvous in at most *4M* time slots, that is $TTR = 4MT$.

4.3 Theorem 3

Under the symmetric model, ETTR of SASJ is upper bounded by $ETTR = (16M - 7)/3$.

4.4 Theorem 4

Under the asymmetric model, any two radios performing SASJ achieve rendezvous in at most *4M* time slots with probability $Pr = G/U$

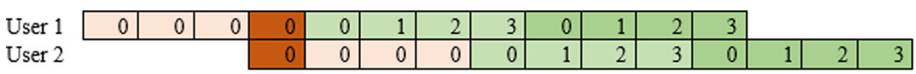


Fig. 2 Simple illustration of SASJ CH scheme

4.5 Theorem 5

Under the asymmetric model, ETTR of EJS is upper bounded by $ETTR = \frac{G}{3U} * (25 - 16M) + \frac{16}{3} * (M - 1)$

5 Theoretical Analysis

5.1 Proof of Theorem 4.1

Generally in all computing system or number theorem, the result of modulo operation on M is the Euclidean division whose remainder R and quotient q satisfy $q, R \in \mathbb{Z}$

$$X = M * q + R$$

Such that $0 \leq R < M$

Note Based on the argument above we simply perform our SASJ CH using X mod M instead of X mod P.

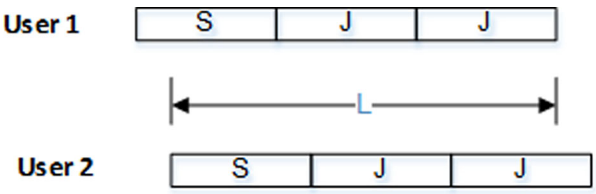
5.2 Proof of Theorem 4.2

Without loss of generality, we assume that radio 1 begins SASJ not later than radio 2. We stated earlier that the hopping step length r is 1. We look at different possible scenarios of user 2 joining the network to seek for potential rendezvous. Let L be the length of overlap between the two radios performing SASJ algorithm. Note that TTR is considered as the time all potential nodes seeking rendezvous join the network to begin performing SASJ.

5.2.1 Symmetric Model with the Same Channel Ranking

Here we make an assumption that tables are ranked similarly, so that radio1's stay channel S is same as radio2's stay channel S.

Fig. 3 Stay–Stay rendezvous for same channel ranking



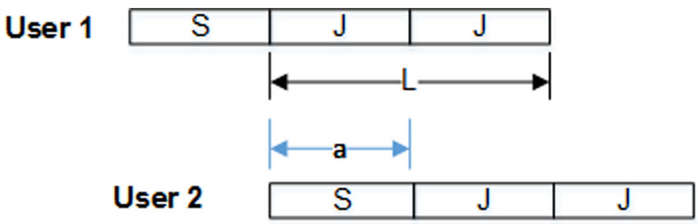


Fig. 4 Stay–Jump rendezvous for same channel ranking

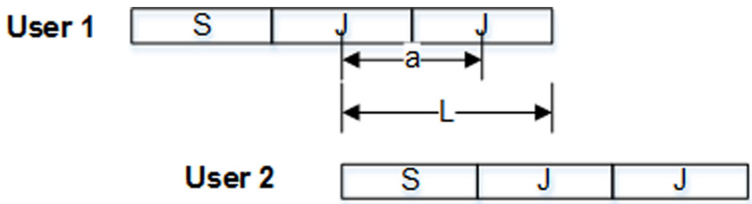


Fig. 5 Stay–Jump rendezvous for same channel ranking

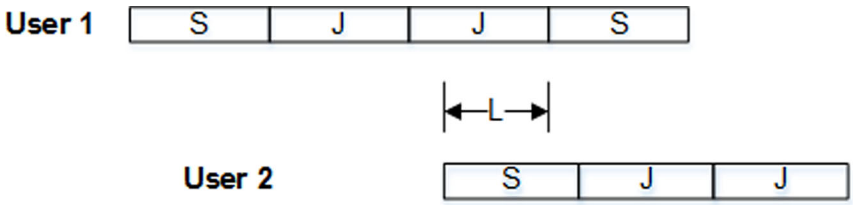


Fig. 6 Stay-Jump rendezvous for same channel ranking

Case 1 $(L > 2M)$

For $L > 2M$ we see that an overlap must exist between radio1 and radio2 stay patterns, and this justifies $TTR < M$ time slots (Fig. 3).

Case 2 $(L = 2M)$

From Theorem 4.1 we can state that the hopping sequence of the radios n is $S_nJ(t) = X \bmod M = U$, where U is the universal set of channels observed by SU1 and SU2, which in this case is M.In the interval a as shown in Fig. 4 rendezvous is bounded since $S_{2S}(t) \cap S_{1J}(t) = S_{2S}(t) \cap U = S_{2S}(t)$. This simply implies that convergence will occurs on radio *2's* stay channel, as such $TTR \leqslant M$ time slots

Case 3 $(L < 2M)$

User 1 on its jump pattern when user 2 joins, see Fig. 5 In the interval a, user 1s jumping sequences is such that $S_{1J1}(t) \cup S_{1J2}(t) = U$, so that rendezvous is bounded within the length of the overlap. That is $S_{2S}(t) \cap U = S_{2S}(t)$ in this case $TTR \leqslant 2M$

Case 4 $(L \leqslant M)$

Similar argument as previous shows that $TTR \leqslant M$ as depicted by Fig. 6

5.2.2 Symmetric Model with Possibility of Different Channel Ranking

In this case $S_1 \neq S_2$

Case 5 $(L > 2M)$

In the interval a, see Fig. 7, $S_{2S}(t) \cap S_{1S}(t) = \varnothing$. Also in the interval b there exist the possibilities that the set of channels $S_{2S}(t) \cap S_{1J}(t) = \varnothing$. Similarly in the interval c $S_{2J}(t) \cap S_{1S}(t) = \varnothing$. As such there exist the possibility of no rendezvous. We introduce a modification that guarantees rendezvous in *4M* time slots as the system rendezvous will not be guaranteed in *3M* time slot. A simple modification is to quickly run an appended hoping sequence R such that in the interval c and d, user 2 which is seeking for the potential neighbour will run the hoping sequence $S_2R(t)$ such that $S_{2J}(t) \cup S_{2R}(t) = U$ (note in the interval c and d). Therefore $S_{2J}(t) \cup S_{2R}(t) \cap S_{1S}(t) = S_{1S}(t)$. System rendezvous is guaranteed on the most prominent channel $S_{1S}(t)$ since $S_{1S}(t) \subseteq U$. Note the appended sequence is $S_{2R}(t) = (Z_{th} - (M - 1)) + r * t \bmod M$. Where Z_{th} is the lowest ranked channel so that the starting index i for the appended sequence is $(Z_{th} - (M - 1))$ by performing the hoping sequence $S_{2R}(t)$ after the *3M* time slot guarantees rendezvous in *4M* time slot.

Case 6 $(L = 2M)$

From Fig. 8, set of channels generated by $S_{1J}(t) = U$ and $S_{2S}(t) \subseteq U$ therefore rendezvous is guaranteed in less than or equal M time slots.

Case 7 $(M < L < 2M)$

As shown in Fig. 9, in the interval a and b, radio 1's hopping sequence is $S_{1J}(t) = U$. We note that rendezvous is guaranteed in less than or equal to M time slot since $S_{2S}(t) \cap U = S_{2S}(t)$.

Case 8 $(L < M)$

This is also similar to case one as shown in Fig. 10 and by similar argument $TTR \leq 4M$. We see from above analysis that for all possible scenarios of two radios hopping across the broad spectrum we have shown that $TTR \leq 4M$.

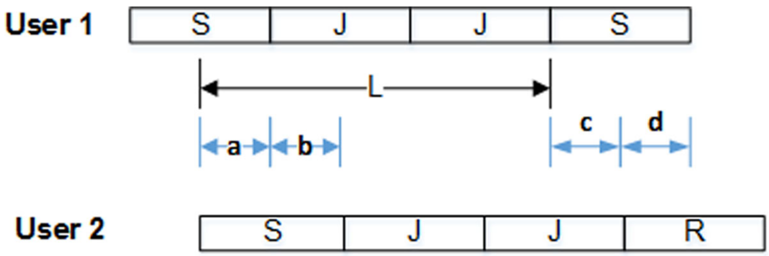


Fig. 7 Stay–Jump rendezvous for same channel ranking

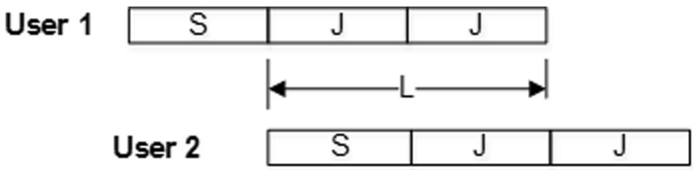


Fig. 8 Stay–Jump rendezvous for different channel ranking

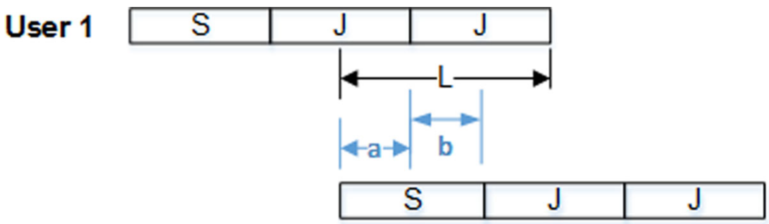


Fig. 9 Stay-Jump Rendezvous for Asymmetric Model

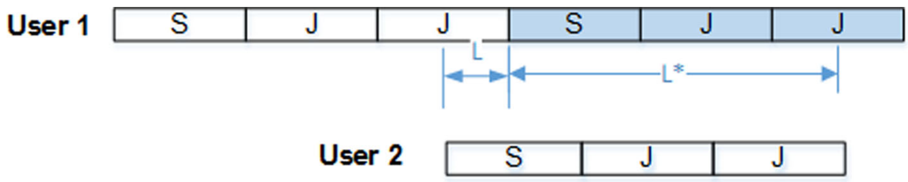


Fig. 10 Stay–Jump rendezvous for asymmetric model

5.3 Proof of Theorem 4.3

We evaluate the performance of the random system using the statistical expectation estimation, described as the Expected Time to Rendezvous ETTR,

$$ETTR = \sum_{1}^{k} x_k P_k(x)$$

Since we considered eight likely scenarios, we combine the occurrence probability to determine the ETTR for the symmetric model. Since the stay channels set lies in the channel set M, the probability of two radios selecting same stay channel is *1/M* and the probability of selecting different stay channel is *(M − 1)/M* , when user two starts it hopping the probability that user one is on its Jump or Stay pattern is 2/3, 1/3, respectively.

Therefore the ETTR for identical channel ranking is

$$ETTR(S_1 = S_2) = \frac{1}{3} * \frac{1}{M} * M + \frac{2}{3} * \frac{1}{M} * M + \frac{2}{3} * \frac{1}{M} * 2M + \frac{2}{3} * \frac{1}{M} * M \tag{8}$$

And for different channel ranking it is

$$\begin{aligned} ETTR(S_1 \neq S_2) = {} & \frac{1}{3} * \frac{M-1}{M} * 4M + \frac{2}{3} * \frac{M-1}{M} * M + \frac{2}{3} * \frac{M-1}{M} * M \\ & + \frac{2}{3} * \frac{M-1}{M} * 4M \end{aligned} \tag{9}$$

The combined ETTR for our system is

$$ETTR = \frac{16M - 7}{3} \tag{10}$$

5.4 Proof of Theorem 4.4

In the asymmetric model, radios SU1 and SU2 seeking potential channels for communication may have divergent hole information arrays, that is SU1 and SU2 may have M_1 and M_2 available channels respectively such that $M_1 \neq M_2$. Let G and U be defined respectively as $G = M_1 \cap M_2$ and $U = M_1 \cup M_2$. As in the symmetric model, each radio constructs its hopping table and we expect rendezvous to occur in *4U* time slot subject to the availability of common channels G with probability *P(C)*

$$P(C) = \frac{G}{U} \tag{11}$$

5.5 Proof of Theorem 4.5

Since Radio 1 and Radio 2 have *M1* and *M2* available channels with G common channels, it means they can select same stay channel with probability $\frac{G}{U}$ and different stay channel with probability $1 - \frac{G}{U}$. Therefore we obtain

$$ETTR = \frac{G}{U} * ETTR(S_1 = S_2) + \left(1 - \frac{G}{U}\right) * ETTR(S_1 \neq S_2) \quad (12)$$

$$ETTR = \frac{G}{3U} * (25 - 16M) + \frac{16}{3} * (M - 1) \quad (13)$$

6 Results Discussion

Table 1 shows popular technique in literature with their derived TTR and ETTR for both the symmetric model as well as the asymmetric model.

Table 1 TTR and ETTR for some rendezvous techniques

Technique	Symmetric model		Asymmetric model	
	TTR	ETTR	TTR	ETTR
SASJ	4M	$\frac{16M-7}{3}$	$4M(M+1-G)$[a]	$\frac{G}{3U} * (25 - 16M) + \frac{16}{3} * (M - 1)$
EJS [8]	4P	$3\frac{P}{2} + 3$	$4P(P+1-G)$	$4P(P+1-G) - \frac{1}{U} * [4PG(P-G) + \frac{G}{2}$
JS [7]	3P	$\frac{5P}{3}$		$2MP(P-G) + (M + 5 - P - \frac{(2G-1)}{M}P$
GOS [5]	$M(M+1)$	$\frac{M^4+2M^2+6M-3}{3(M^2+M)}$		
CRSEQ [21]	$P(3P-1)$			

[a] TTR as derived in [8] but we performed our SASJ using M and not P

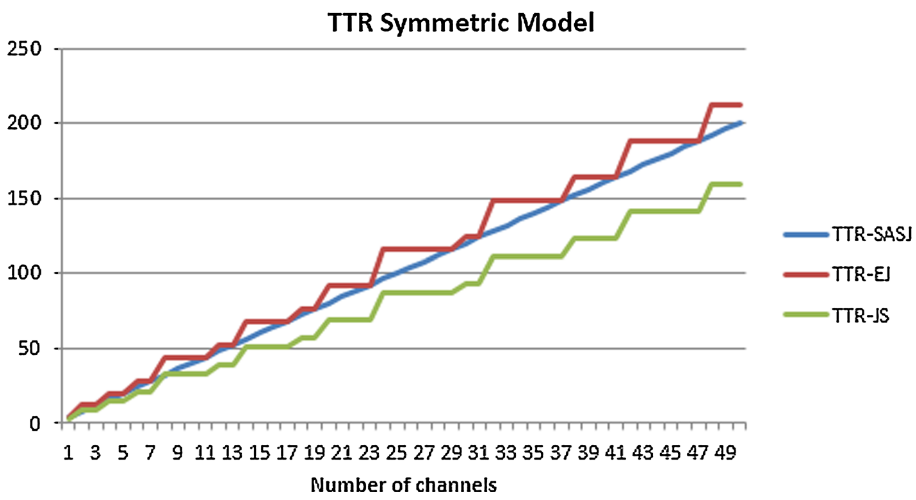


Fig. 11 TTR for symmetric model

Figure 11 shows a comparison of the TTR for SASJ with that of EJS and the JS Algorithm under the symmetric model. We see that our technique slightly outperformed the EJ in terms of its reduced TTR. However, we note that although JS did better in terms of its TTR, Fig. 12 revealed that JS performed less when we compare it with likelihood to rendezvous, ETTR. The implication of this is that there exist scenarios for which JS may not converge. Figure 13 shows a comparison of the TTR for asymmetric model of the three techniques, again SASJ scheme showed a reduced TTR when compared with both EJ and

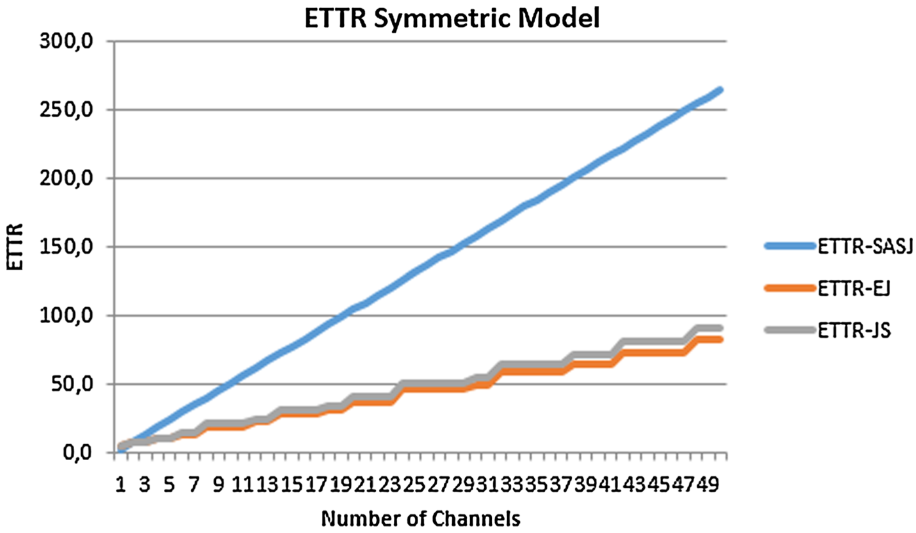


Fig. 12 ETTR for symmetric model

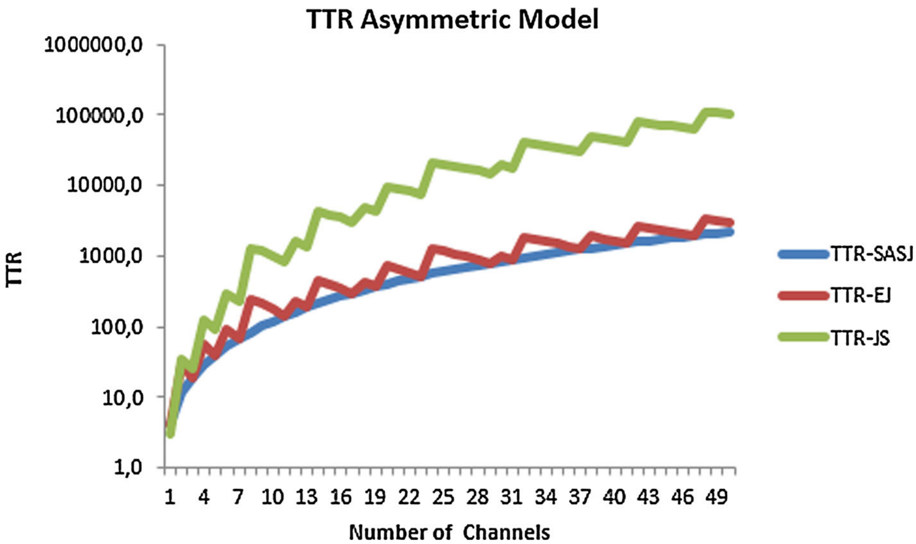


Fig. 13 TTR for symmetric model

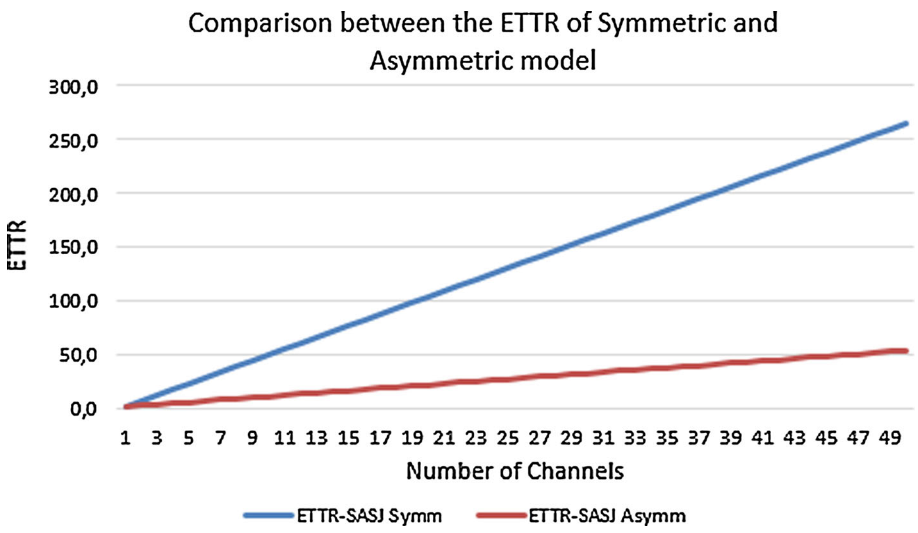


Fig. 14 TTR for symmetric model

JS. Figure 14 shows a comparison of ETTR for both the symmetric model and the asymmetric model we see that the ETTR for symmetric model will always be higher than that of the asymmetric model. This is only rational as both radios in the symmetric model have same hole information arrays.

7 Conclusion

The deployment of CR for Ad-Hoc Networks will require that nodes exchange control signals among themselves. In realizing this, researchers alike agrees on the need for a dynamic control channel selection technique. This dynamic control channel selection technique offers the possibility of control channel reselection in the event of jamming or security attacks as opposed to the fixed control channel selection technique. This paper presents a new CH scheme, the SASJ. This scheme deposits pheromone trail on its most prominent channel, updates its hole information array, rank channels and constructs CH scheme. We showed by means of theoretical analysis that our SASJ hopping scheme guarantees system rendezvous in a bounded time. TTR and ETTR were also derived for both the asymmetric and the symmetric models. We showed an overall improvement in TTR and ETTR.

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