Channel-Change Games for Highly Interfering Spectrum-Agile Wireless Networks

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***Abstract*— The proliferation of wireless networks on unlicensed communication bands leads to coexisting networks, creating interference problems. In this paper, interference problems for spectrum-agile networks are addressed by allowing the networks to dynamically change channel. For insight into dynamic channel-change strategies, we model the networks as autonomous players in a multistage non-cooperative game-theoretic model. Here the networks are assumed to be highly interfering, i.e., when two or more networks exist on a single channel they cannot successfully carry traffic. Each network seeks to minimize its time to find a clear channel. The game-theoretic analysis reflects the motivations and choices of independent, rational, selfish decision makers that do not trust one another. We analyze the game-theoretic solutions appropriate for an untrusted environment, and compare the results with socially optimal decisions that would maximize the expected benefit of all coexisting networks in a trusted environment.**

I. Introduction

In recent years, there has been a proliferation of wireless networks on unlicensed communication bands, such as the ISM bands at 2.4 GHz. Multiple networks may find themselves using the same communication band at the same time, resulting in interference problems [10], [13]. One way of addressing large-scale spectrum sharing is through the use of smart, spectrum-agile (or cognitive) networks that can dynamically switch communication channels based on interference on the current channel. The decision-making can be done in the access point of each network.

In our dissertation [15], we have introduced the modeling of channel-change decisions using game theory [4], [12] by developing five models to capture different channel-change scenarios. We have focused on simple scenarios to provide initial insight. In this paper, two of these models are presented. The other models, using different assumptions, are presented in [16], [17]. We also compare game-theoretic decisions to idealized, socially optimal decisions that maximize the expected benefit of all coexisting networks.

Game theory has been used extensively to model strategic decision-making in economics [14], political science [9], and other social sciences. Recently, it has been used to model several aspects of wireless networks [1]. Mangold et al [8], [3] have used game theory to model channel-sharing decisions by coexisting wireless networks, but do not address channel change. Game theory has also been applied to adaptive channel allocation [11], and to access control in single Aloha-like networks [2], [6], [7].

In Section II, the two channel-change decision-making scenarios are presented. In Section III, our multi-stage game formulation is described, while Sections IV and V present the details of the two decision-making models. The two models are compared in Section VI, and some conclusions are presented in Section VII.

II. Channel-Change Scenarios

We model two similar, interfering networks that find themselves residing on the same wireless communication channel. We consider scenarios of high network interference where we assume channel sharing leads to blocking. Each coexisting network has the option of changing to a new channel to make progress. However, there is a time delay in moving from one channel to another, known as the *channel-change overhead* and represented as v with $v>0$. The two networks play a game of "chicken" to see who blinks first and therefore pays the channel-change overhead cost. We have focused on high interference scenarios because dynamic channel change is more relevant here, and the assumption simplifies the analysis.

Two channel-change scenarios are presented, based on the number of available channels. In order to first focus on the simplest models, we consider a *two-network many-channel* scenario in which the two interfering networks have a large number of alternate channels for switching, and a *two-network two-channel* scenario that is more constrained. In the many-channel case, even if the coexisting networks simultaneously change their channels, they do not interfere with each other again. However, in the two-channel scenario, the networks will interfere again after simultaneous channel change.

The networks are assumed to have intelligent access points, capable of making dynamic decisions regarding which channel to use. The networks are further assumed to have a protocol whereby any network can request its member devices to dynamically switch to a new channel.[1] We assume that the

[1] This capability has already been defined in the IEEE 802.11h standard, where the access point sends information regarding channel change in its

access points make decisions expected to achieve the best payoffs for their own networks, consistent with game-theoretic assumptions.

III. Game Formulation

Game-theoretic modeling shows the decisions made by rational decision makers maximizing their own benefit in various competitive situations. Channel-change decision-making is modeled using multi-stage games, since it is expected to be an ongoing activity as traffic conditions on different channels change over time.

To model multi-stage decision-making, each network considers time as a sequence of "time slots". One stage of decision-making is carried out in a time slot. At the beginning of an arbitrary time slot, two similar networks find themselves coexisting on a single channel. Each network has a message to transmit, where the messages are assumed to be of equal duration. Assuming high interference (channel blocking), neither network can successfully transmit as long as both networks coexist on the same channel.

At the beginning of each time slot, each network can either choose to change channel (C), or to remain (R) on the current channel and attempt transmission. If a network chooses to change channel, it incurs a channel-change delay equal to v time slots. If the network chooses to remain, it either experiences a blockage or a clear channel, depending upon whether the other network has chosen to remain or change respectively. In the case of mutual blockage, the game must be played again in the next time slot. Each network has the objective of minimizing its *channel acquisition cost* defined as the total expected delay incurred until achieving a clear channel for transmission.

IV. Two-Network Many-Channel Game

A. Game Representation

We use multi-stage games with a simple structure known as *multi-stage games with observed actions*[2] [4] (p. 70). All stages of the game are identical, with each stage being a strategic-form game with complete information [4] (p. 4). The two interfering networks, Network 1 and Network 2, are the players of the game. The set of players ϑ is given by {1, 2}. The choice of actions for each player is the same: *Change* to another channel or *Remain* on the current channel. The set of actions is given by $A_1 = A_2 =$ {Change, Remain}. In each stage of the game, both players simultaneously choose their actions. An action profile represents the combination of the actions taken by each of the players. The set of all possible action profiles in any stage is given by {(C, C), (C, R), (R, C), (R, R)}, where C stands for *Change* and R for *Remain*.

The *cost*[3] to each player depends on the selected action profile since each player is affected by its action, as well as the action taken by the other player. For example, $u_1(C, C)$ represents the cost of the action profile (C, C) for network 1. The goal for each player (network) is to minimize cost, or the time to acquire a clear channel.

The *two-network many-channel* game is represented by the matrix shown in Fig. 1. Each cell of the matrix represents the costs incurred by networks 1 and 2 respectively for the action profile represented. The value of $u_1(C, C)$ is given by the channel-change cost v. This is a result of our assumption of many available channels, where, if both networks change channel, they always acquire clear channels by switching to different channels. Similarly, $u_1(C, R)$ is also given by v since network 1 changes channel. However, $u_1(R, C) = 0$ because network 2 changes to another channel, while network 1 has no further delays since it is left alone on the current channel. The costs for network 2 are obtained using similar reasoning, since both networks are identical. The three action profiles discussed so far represent terminal states because the game ends. The last case, $u_i(R, R)$, is more complex since the game continues.

		Network 2	
		Change	Remain
Network 1	Change	v, v	v, 0
	Remain	0, v	1+u, 1+u

Fig. 1: Stage game for the two-network channel-change game with many channels and pure strategies. v gives the channel-change overhead, and u the cost of the full multi-stage game.

The action profile (R, R) leads to the same situation as at the start of the game, in which two networks are on one channel. Once again, the two networks face an identical game and an identical time cost before transmission can begin. Let us assume that the total cost incurred by a network before it exclusively acquires a channel is $u_1 = u_2 = u$ time units. Then we say that the cost of the full multi-stage game is given by u time units. Since choosing the action profile (R, R) leads to the same state as at the start of the game, the same time delay of u units remains after the current stage. In addition, a delay of 1 time unit for the current stage has to be added. Hence, the cost for this action profile, $u_1(R, R)$, is given by $1+u$ for each player.

B. Game-Theoretic Analysis

Let us examine how this game is played by rational players (networks) using the solution concept of *Nash Equilibrium* (NE). A Nash Equilibrium is an action profile a^* such that

beacon and specifies the number of beacon intervals after which the change will be effective.

[2] Referred to as an *extensive game with perfect information and simultaneous moves* in [12] (p. 206).

[3] Note that in game theory, usually the term "utility" or "payoff" is used instead of "cost" because it represents a benefit that the player would like to maximize. In this paper, since the objective of the players is to minimize the channel acquisition time, the term "cost" is used instead. However, in a slight abuse of notation, we continue to use the symbol "*u*" to represent this cost.

each player's action is an optimal response to the other players' actions [12] (p.23). There is no motivation for a player to deviate unilaterally from this action profile.

Let us look at the selection of actions in each stage of the multi-stage game. Each network would like to minimize its delay cost. If network 2 changes its channel, network 1 prefers to remain on the current channel, since $v > 0$ (refer to Fig. 1). However, if network 2 remains on the current channel, network 1 prefers to change channel as shown below.

Condition $1+u > v$

We show that the condition $1+u > v$ always holds. Suppose this condition does not hold, i.e., $1+u \leq v$. In this case, network 1 would always choose the action *remain* irrespective of whether network 2 chooses *change* or *remain*. Using similar reasoning, network 2 would also always choose *remain*. Thus (R, R) would always get selected, making it a dominant action profile. But if the networks keep playing (R, R), no one can transmit due to channel blocking. The cost of the game, u, becomes infinite, leading to a contradiction. Hence, we know that $1+u > v$. Q.E.D.

Thus there are two stable action profiles in this game: (R, C) and (C, R). These two action profiles are also the two Nash Equilibria (NE) using pure strategies. We notice that these two NE are not symmetric. When one network chooses *change*, the other chooses *remain*, and vice-versa. Since the two networks are assumed identical, they should be able to choose the same actions. However, this is not possible with pure strategies. Hence we consider using a mixed strategy by assigning probabilities to each of the two pure strategies. By symmetry, both networks will assign the same values to these probabilities.

		Network 2: Change	Network 2: Remain
Network 1	Change	v, v	v, 0
	Remain	0, v	1+U, 1+U

Fig. 2: Stage game for the two-network channel-change game using mixed strategies. Similar to Fig. 1, except that the expected cost of the full game, U is substituted for the pure strategy cost u. v gives the channel-change overhead.

The stage game using mixed strategies is shown in Fig. 2. Note that the only difference with Fig. 1 is that the cost of the remaining game u is replaced by the expected cost U, since the cost depends on the probability with which the actions *change* and *remain* are selected.

To determine the stable operating point for this multi-stage game, we find its Nash Equilibrium (NE). Using mixed strategies, we assume that both networks 1 and 2 use a probability p of changing channel and probability $1-p$ of remaining on the current channel. We first find U_C, network 1's expected cost to change channel. Considering the first row of Fig. 2, we obtain U_C using p and $1-p$ as weights for the $u_1(C, C)$ and $u_1(C, R)$ costs:

$$U_C = pv + (1-p)v = v \tag{2}$$

Similarly, considering the second row of Fig. 2, the expected cost for network 1 to *remain* on the current channel is given by U_R as:

$$U_R = (1-p)(1+U) \tag{3}$$

Network 1 will choose to *change* channel if $U_C < U_R$ and to *remain* on the current channel if $U_C > U_R$. When $U_C = U_R$, network 1 has no preference between the two strategies. Under this condition, network 1 has the same cost whether it chooses the pure strategy of *change* or *remain* or some mixed strategy which is a combination of the two. In particular, it can choose the mixed strategy of $(p, 1-p)$ and obtain the same expected cost. Thus, it has no motivation to deviate from the mixed strategy of $(p, 1-p)$ given that network 2 has chosen this mixed strategy. This is the Nash Equilibrium condition. Under NE, the two costs are equal, i.e. $U_C = U_R = U$. Applying this condition to (2) and (3), we can find the NE probability p^* as:

$$p^* = \frac{1}{1+v} \tag{4}$$

The NE probability of changing channel depends on the channel-change overhead. As we would expect, if the cost of changing channel v goes up, the probability of changing channel p^* comes down. From the symmetry of the game, both networks will use the same probability p^*. The expected cost U^* at the NE can be found from (2):

$$U^* = v \tag{5}$$

Under Nash Equilibrium, the expected delay in exclusively acquiring a channel is the same as the channel-change time. The equations for p^* and U^* have also been verified by using an alternate approach [15].

C. Socially Optimal Analysis

The results of game-theoretic analysis obtained above are compared to those obtained from analyzing "socially optimal" decisions made by an abstract "centralized" decision maker. The socially optimal decision maker promotes the best interest of all networks, rather than the self-interest of any individual network. It assigns a channel-change probability of p to each of the two networks, instead of allowing each of them to non-cooperatively choose their own channel-change probabilities. We will see how the socially optimal channel-change probability (p') compares to the game-theoretic value p^* derived in the previous section. Note that in this paper, the terms "socially optimal" and "centralized" are used in analogously, but the decisions are not made by a single centralized entity such as an access point.

The socially optimal channel-change probability (p') is obtained by minimizing U, the total expected channel acquisition delay cost for each network. Let U_C and U_R be the expected *change* and *remain* delay costs for both networks as before. Then, U is given by:

$$U = pU_C + (1-p)U_R \tag{6}$$

Substituting U_C and U_R using (2) and (3) and minimizing U with respect to p gives the socially optimal channel-change probability $p' > 0$ and the corresponding delay cost U' as:

$$p' = \frac{\sqrt{1+2v}-1}{v} \tag{7}$$

$$U' = \frac{\sqrt{1+2v}+v-1}{2} \tag{8}$$

D. Comparison and Cost

The game-theoretic and centralized change probabilities, p^* and p', are shown in Fig. 3. We see that the centralized decision maker forces much more change, i.e. $p' > p^*$.

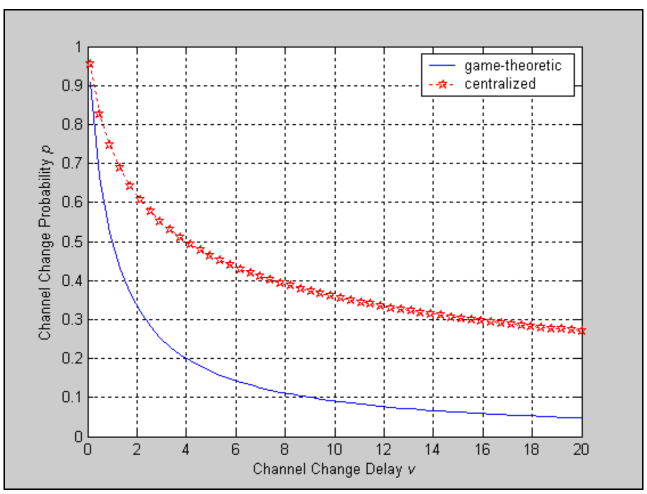

Fig. 3: Comparison of channel-change probability in game-theoretic and centralized, socially optimal decisions for two networks and many channels. The centralized decision maker forces more change.

The game-theoretic and centralized delay costs, U^* and U' are plotted in Fig. 4. Socially optimal decision-making provides lower expected cost than non-cooperative, game-theoretic decision-making. The price paid for self-interested game-theoretic decisions is given by U^* - U'. This cost can be viewed as an example of the Tragedy of Commons [5], where a shared resource is used less effectively when users are optimizing their self-interest. However, we note that self-interest is the rational choice of independent networks in an untrusted environment.

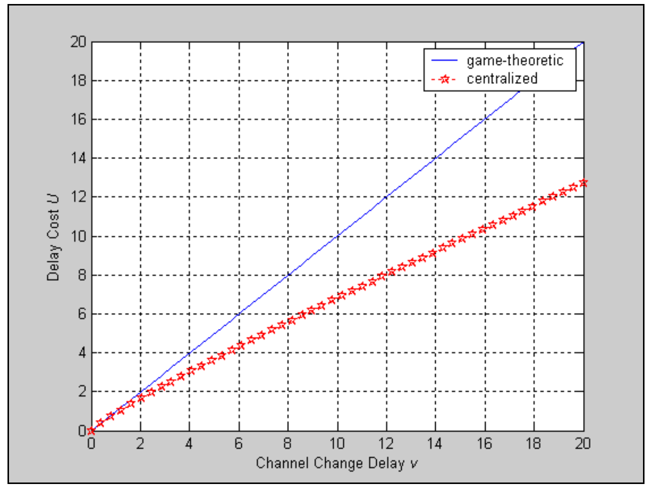

Fig. 4: Comparison of delay cost in game-theoretic and centralized, socially optimal decisions for two networks and many channels. The centralized decision maker gives a lower delay cost.

V. Two-Network Two-Channel Game

A. Game-Theoretic Analysis

In the previous game, a large enough number of alternate channels was available, so that every channel change resulted in a network finding an unused channel. We now limit the total number of available channels to two. All other aspects of the decision-making scenario are the same as before. With only two channels available, a simple scenario of channel contention is created when both networks change their channels simultaneously. This scenario introduces the more realistic expectation that changing a channel does not always solve the interference problem, and further channel changes may be necessary. We study how the channel-change probability and channel acquisition time are affected by this new constraint.

		Network 2	
		Change	Remain
Network 1	Change	v+U, v+U	v, 0
	Remain	0, v	1+U, 1+U

Fig. 5: Stage game with mixed strategies for two channels. The main difference with many channels in Fig. 2 is that when both networks change channels, they interfere with each other again and the game continues.

The *two-network two-channel* game using mixed strategies is shown in Fig. 5 (equivalent to Fig. 2). The only difference between Fig. 2 and Fig. 5 is in the cost for the action profile (C, C). Now, when both networks change channel, they find themselves blocking each other on the new channel as well. Thus, they are in the same situation as at the start of the game, but on a different channel, and have incurred an additional delay of v time units each due to channel change, with $v>0$ as before.

Using the same procedure as before, we determine the stable operating point for the game by finding the Nash Equilibrium (NE) values $p*$ and $U*$ for this game:

$$p* = \frac{2 + v - \sqrt{4v + v^2}}{2} \tag{9}$$

$$U* = \frac{v + \sqrt{4v + v^2}}{2} \tag{10}$$

B. Socially Optimal Analysis and Comparison

Using the same procedure as before for centralized, "socially optimal" decisions, the expressions obtained for p' and U' with two channels are:

$$p' = \frac{1}{\sqrt{v} + 1} \tag{11}$$

$$U' = \sqrt{v} + \frac{v}{2} \tag{12}$$

The comparison of game-theoretic and socially optimal results for the two-channel scenario are shown in Fig. 6-7. As with many channels, we see that the socially optimal decision maker forces much more change, i.e. $p' > p*$ in Fig. 6, resulting in lower delay cost as shown in Fig. 7.

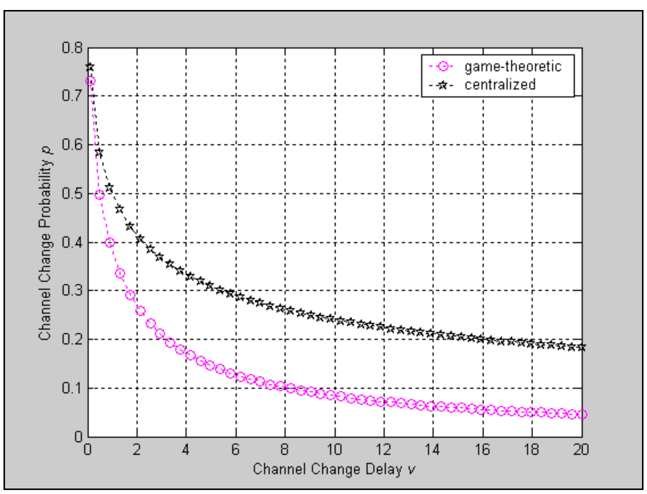

Fig. 6: Comparison of channel-change probability for game-theoretic and centralized decisions with two channels. The game-theoretic decision maker always has a lower channel-change probability.

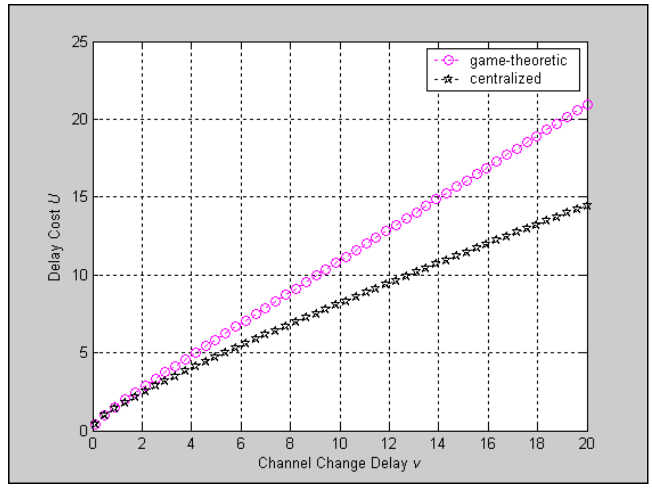

Fig. 7: Comparison of delay cost for game-theoretic and centralized decisions with two channels. The game-theoretic decision maker always has a higher delay cost.

VI. Comparison of Models

For comparison, the results obtained for many channels and two channels are summarized in Table I.

TABLE I: SUMMARY OF RESULTS

	Two-Network Many-Channel Game	**Two-Network Two-Channel Game**
p*	$\frac{1}{1+v}$	$\frac{2+v-\sqrt{4v+v^2}}{2}$
U*	v	$\frac{v+\sqrt{4v+v^2}}{2}$
p′	$\frac{\sqrt{1+2v}-1}{v}$	$\frac{1}{\sqrt{v}+1}$
U′	$\frac{\sqrt{1+2v}+v-1}{2}$	$\sqrt{v}+\frac{v}{2}$
Cost *U - U′***	$\frac{1+v-\sqrt{1+2v}}{2}$	$\frac{\sqrt{4v+v^2}}{2}-\sqrt{v}$

The comparison of game-theoretic channel-change probabilities for two channels and many channels is shown in Fig. 8. We see that the channel-change probability for two channels is always lower than that for many channels. This is intuitive, because with only two channels available, the networks could interfere again by changing channel, and hence the motivation to do so is lower. As v gets larger, the difference between the two reduces.

The comparison of the NE delay cost $U*$ for two channels and many channels is shown in Fig. 9. The cost for two channels is always higher than for many channels. This is also intuitive because one would expect higher delays with fewer channels.

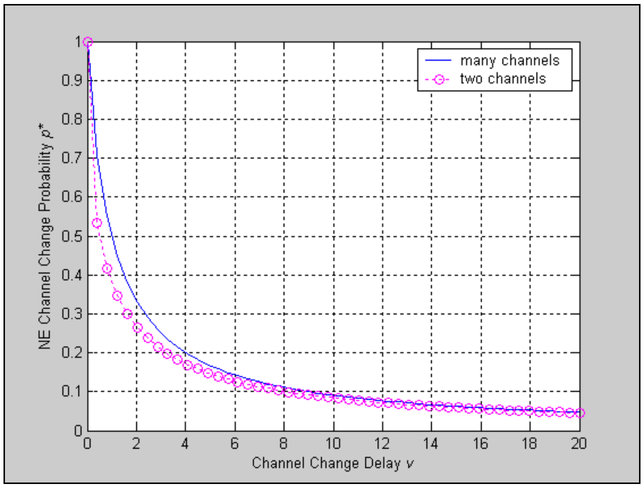

Fig. 8: Game-theoretic NE channel-change probability comparison for many-channel and two-channel models. With two channels, the probability is lower for low values of v.

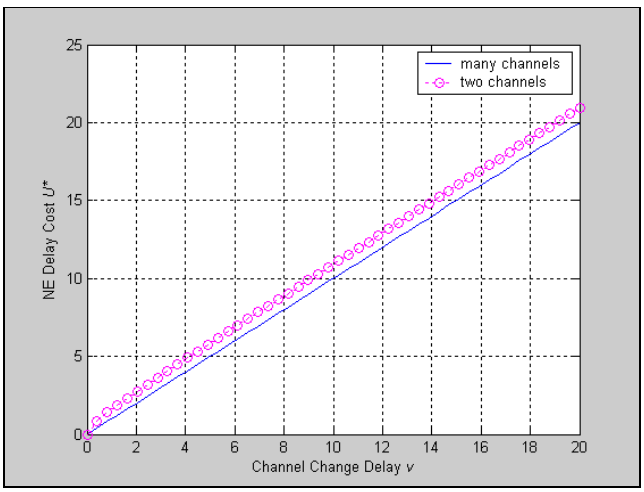

Fig. 9: Game-theoretic NE delay cost comparison for many-channel and two-channel models. With two channels, the delay cost is always slightly higher.

VII. CONCLUSION

We introduce the idea of modeling dynamic channel-change decisions as games to handle the problem of interference from coexisting spectrum-agile wireless networks. In this paper, we have presented two two-network, multi-stage channel-change games. We have extended this work to multiple interfering networks in [17]. We have also removed the channel blocking assumption for two single-stage models in [16]. More complex models, including multi-stage models without channel blocking, and simulation work are left for the future.

The issue of dynamic channel change is very relevant in unlicensed bands, since they are shared by many different networks. Further, unlicensed usage is expected to grow as more and more licensed bands start supporting unlicensed secondary users. This will make dynamic channel change even more important in the future. Incorporating channel change is also helpful in allowing the easy set up of access points, especially in large installations, because channels do not need to be manually pre-assigned. The results of this paper provide some insight into dynamic channel-change strategies for intelligent spectrum-agile wireless networks.

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