Spectrum Leasing for Micro-operators Using Blockchain Networks

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Abstract. This paper introduces a spectrum sharing system for Micro Operators (MOs) using the blockchain network. In order to satisfy different network requirements for each service, the license for spectrum access should be dynamically allocated to the required spectrum bandwidth. We propose a spectrum lease contract for MOs to share spectrum with the Mobile Network Operator (MNO) is performed through the blockchain networks. Main reasons for applying the blockchain network to the spectrum sharing system are as follow. First, the blockchain networks share database with all participants. Second, networks have mutual trust among all participants. Third, it needs no central authority. Fourth, automated contract execution and transaction interactions are possible. The blockchain usage in the MO-based spectrum sharing system and the detailed process of spectrum lease contract are proposed. Then, the economic effects of spectrum sharing system for MOs is analyzed. The MO can be profitable by getting involved in the blockchain to take reward for a Proof of Work (PoW) and providing wireless service to its users.

Keywords: Spectrum sharing · Micro-operator · Blockchain
Dynamic Spectrum Access · Optimization · Network economics

1 Introduction

As the age of 5G approaches, increasing demand for Enhanced Mobile Broadband (eMBB), Ultra-reliable and Low-latency Communications (uRLLC), and Massive Machine Type Communications (mMTC) require more radio resources [1]. To satisfy those demands, securing available spectrum is one of the most important issues. The bands that are mainly studied in academic and industrial sectors are divided into mmWave and sub 6 GHz band. However, there are some engineering issues such as directivity and sensitivity to blockage to use mmWave in practical communication systems [2]. To compensate limitations and disadvantages of mmWave, it is important to utilize the existing spectrum band. Unfortunately, the lack of available spectrum is widely known [3].

Spectrum sharing concept is one of promising wireless technologies to make full use of the spectrum bandwidth that is allocated to license holders [4]. The key role of spectrum sharing is to look for balance among different services with their various Quality-of-Service (QoS) and system temporal dynamics so that the spectrum is efficiently utilized [5]. As an attempt to construct an efficient spectrum sharing system in a

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real environment, there have been researches on how to use idle spectrum bands such as TVWS [6]. Based on a decade of profound spectrum sharing research, a couple of practical spectrum licensing-based sharing models have been emerged. Citizens Broadband Radio Service (CBRS) [7] and Licensed Shared Access (LSA) [8] are such examples. Efforts to more efficiently use a limited spectrum have led to Micro Operator (MO) research beyond CBRS and LSA [9].

The concept of MO is local service delivery in wireless networks to build indoor small cell communication infrastructure and to provide context related vertical contents [10]. Cell densification and network slicing realize the service of MO. It is inefficient that assigning exclusive rights to MOs whose service region and time are specific. Therefore, it is persuasive to receive a certain spectrum of authority distribution from existing Mobile Network Operator (MNO). Spectrum can be efficiently used through dynamic spectrum allocation to support the services such as automated medical services, smart factories and VR/ARs in tight space.

With the emergence of Bitcoin proposed by an anonymous engineer named Satoshi, the blockchain technology, which is a distributed ledger system, attracted considerable attention. The blockchain is a system where all clients equally own the distributed ledger and update the new information. Information of transactions between users are stored permanently in the chain form of blocks. The blocks are copied and shared among clients across the networks. Reliability of data is guaranteed by a mechanism of consensus of blockchains [11]. Unlike the conventional method based on centralized authority [12], the blockchain guarantees stability from malicious attacks even in the trustless environment. Since there is no central administrator, single point of failure and attack is technically immune [13].

Blockchains are being discussed in various distributed systems and multiple access network scenarios, e.g., smart grid systems [14], vehicular networks [15], mobile edge computing [16], Internet-of-Things (IoT) [17] and spectrum sharing system such as CBRS [19]. In particular, MO based spectrum sharing systems that require short term transactions on spectral license holders like MNOs, can utilized the advantages of blockchains. Sensing values stored in a block serving as a distributed database has potential for Dynamic Spectrum Access (DSA), Peer-to-Peer (P2P) transaction.

In this paper, the spectrum sharing system where MOs Ware granted DSA rights by using the blockchain network is proposed. A reasonable reward system that can maintain the blockchain network ecosystem is also designed. Then, the detailed process of wireless services from MOs to the end is described.

2 Blockchain Technology

The blockchain comes from the birth of a cryptocurrency called Bitcoin in 2008, proposed by Satoshi, an anonymous individual or a group [11]. The fundamental idea of blockchain is that blocks serving as databases are continually created and updated in a chain [13]. Each node in the blockchain network has the same verified transactions, information, and contracts etc. The public ledgers, which are distributed databases shared across all participants, are tamper-proof, cryptographically secured, and permanent records of all the transactions that ever took place among the participants. The information about every transaction completed is shared and available to all participants, which imply that there is no need for a central certification authority anymore.

The reason that the blockchain can be kept constant is that the information in the blocks is not counterfeit. There are various consensus algorithms to guarantee this trust. A Proof of Work (PoW) is described as the most popular algorithm being used by currencies such as Bitcoin and Ethereum [20]. Blockchains use PoW to elect a leader who will decide the contents of the next block. In PoW procedure, nodes who want to be elected as a leader have to solve a simple mathematical quiz. The mathematical quiz is finding out what a number *nonce* is. Since the hash function is cryptographically secure, trying all possible combinations of *nonce* is the only way. The node who firstly solve the aforementioned problem has the right of updating the blockchain update [21]. These solvers are called a *minor*. Whenever a new block is generated, that winner node gets rewarded with transaction fees and system rewards. The other nodes verify validity of the block by checking whether the nonce is the right answer.

Then, our motivation of applying the blockchain technology to the MO-based spectrum sharing system is as follows: First, MOs and MNOs should make sure that the spectrum sharing system is running securely and reliably. This is possible because all nodes participating in the block chain have a shared database called ledgers. In addition, the interference from incumbent users sensed by an MO, which has duty protecting MNO service, stored in the block and shared with MNOs. If MNO leases the spectrum bandwidth considering interference level, spectrum utilization is maximized.

In situations where spectrum bands are traded, a complete trust relationship between stakeholders is needed. In the blockchain network, the record of transactions only can be modified when all *nonce* of blocks are known. But, it is technically impossible knowing all numbers n simultaneously. This property prevents transaction records from forgery.

3 MO-Based Spectrum Sharing System

Considering the wireless network, there are a number of MOs that provide the various local services. One MNO provides the primary access. The MNO already has authorized spectrum band allocated from the government. MOs lease the spectrum from MNO because they do not have exclusive spectrum usage rights. From the perspective of spectrum license holders like MNO, the license holders can share their spectrum to generate additional revenue.

3.1 Blockchain Usage in Spectrum Sharing System

The MO provides local services via spectrum sharing through the blockchain network as shown in Fig. 1. The blockchain network is based on a distributed P2P network among user nodes, and mining nodes [19]. In the blockchain network, user nodes are composed of MO and MNO. Dedicated miners not associated with any spectrum leasing are defined as mining nodes. When the spectrum license lease is approved as a smart contract in the blockchain, the actual deployed MOs can provide each local service to the users.

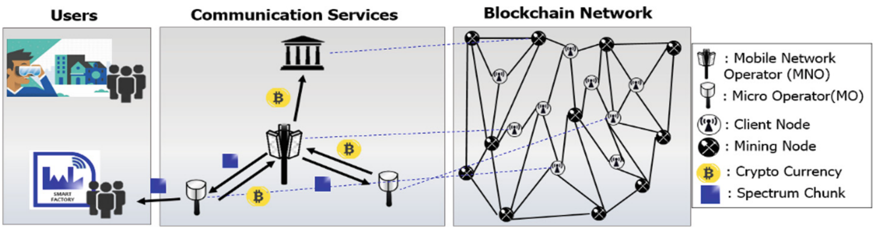

Fig. 1. Spectrum sharing system based on blockchain network

For the spectrum lease transaction to take place through the blockchain, the client nodes transact with cryptocurrency which we call as *Sharecoins*. It can be exchanged with cashes. It is assumed that base currency for spectrum leasing transactions is *Sharecoin*. It is not only used as bids for leasing spectrum but also serves as a reward for efforts to update the blockchain.

The reward received by the winning node for the block generation should be set appropriately. The rewards for mining are defined as follows: The winner node who the fastest accomplishes PoW gets reward as *Sharecoins*. The reward is given for block generation and transaction validation fee on the block. The other nodes that fail to conduct fastest PoW cannot receive any reward. Reward can be obtained in proportion to the mining capacity of the node versus the total mining capacity in the long-term perspective. The spectrum lease transaction in the blockchain network is conducted by several network components as follows:

- Mobile Network Operator (MNO): A spectrum license holder from the authorized organization. It participates as a client node in the blockchain network. It performs spectrum leasing transaction in the blockchain network. *Sharecoin* is given for the reward of spectrum leasing.
- Micro Operator (MO): Provide wireless communication service to users with spectrum bandwidth leased from MNO. MO is also a client node that performs the actual spectrum license transaction with its *Sharecoin* in the blockchain network. The MO participates in mining to maintain blockchain. As reward of mining, MO gets *Sharecoin*.

3.2 System Model

The wireless communication service market consists of MNO, MO and users of MO. We assume there is plenty of miners that guarantees security our blockchain. This means the blockchain network is maintained even if MO does not perform PoW at all. From now on, we refer wireless communication service as service. In Fig. 2, the MNO determines the unit price for the shared spectrum. The MO jointly determines the service price and involvement to maintaining blockchain to maximize its net profit. Each user of MO maximizes its payoff by determining how much it leases the spectrum from MO. The profit maximization is solved by applying the concept of backward induction as shown in Fig. 2 [22].

Fig. 2. The spectrum leasing contract

Let p_M is the unit price of the shared spectrum bandwidth for service. Note that the unit price for leased spectrum p_s and the spectrum bandwidth for MO W is determined by MNO. The parameters p_m and p_s is bounded in $[0, 1]$. Each user demands the quantity of spectrum denoted by Q. As a result, MO's profit is $(p_M - p_s)Q$.

Because MO manages its spectrum sharing system with blockchain, MO processes PoW of its blockchain. Let p_w is rewards for the PoW. MO's reward p_w is directly proportional to the computing resource allocation for PoW denoted by m. Computing resource allocation for PoW, m is a value between 0 and 1. If m is one, MO allocates all its computing resources to PoW. Otherwise, MO allocate computing resource to service. We denote γ as redundant computing resource for providing service. Accordingly, if m exceeds γ, the quality of service deteriorates.

MO jointly chooses the optimal unit price of spectrum bandwidth p_M and the computing resource allocation for PoW m to maximize its profit. Then the maximum profit of MO is as follows:

$$\max_{0 \le p_M \le 1, 0 \le m \le 1} \pi^{MO}(p_M, m) = max(p_M - p_s)Q(p_M, m) + mp_w. \tag{1}$$

The *service* type of users is varies depending on MO's local service. The service type represents different willingness to pay of each user which is denoted as v. Assume that the parameter v is uniformly distributed in $[0, 1]$ [23]. The utility of user with willingness to pay v is defined as $u(v, b, m)$ when spectrum bandwidth is b and the computing resource for PoW of MO is m. If m is lower than γ, the utility of user is retained. But m is greater than γ, the utility of the user is reduced. Then $u(v, b, m)$ is:

$$u(v, b, m) = \begin{cases} v \ln(1 + b), & if\, 0 \le m < \gamma, \\ v \ln\left(1 + \left(\frac{1-m}{1-\gamma}\right) b\right), & if\, \gamma \le m \le 1. \end{cases} \tag{2}$$

The MO imposes users a linear payment p_M per unit spectrum bandwidth. Then, net utility of the user with service type v is the difference of its utility and payment, i.e.,

$$u(v, b, m) = \begin{cases} v \ln(1 + b) - p_M b, & if\, 0 \le m < \gamma, \\ v \ln\left(1 + \left(\frac{1-m}{1-\gamma}\right) b\right) - p_M b, & if\, \gamma \le m \le 1. \end{cases} \tag{3}$$

4 Numerical Analysis

In this section, the utility of users and the profit of MO are analyzed from an economic perspective in the proposed spectrum sharing system

4.1 Users of MO' Demand

The optimal amount of spectrum bandwidth that maximizes the net utility of user is

$$b^*(v, p_M, m) = \begin{cases} \frac{v}{p_M} - \frac{1-\gamma}{1-m}, & \text{if } \left(\frac{1-\gamma}{1-m}\right) p_M \leq v \text{ and } m > \gamma, \\ \frac{v}{p_M} - 1, & \text{if } p_M \leq v \text{ and } m \leq \gamma, \\ 0, & \text{otherwise}. \end{cases} \tag{4}$$

For a user who has willingness to pay v, the maximum of the Eq. (2) is:

$$u(v, b^*(v, p_M), p_M, m) = \begin{cases} v \ln\left(\frac{1-m}{1-\gamma} \frac{v}{p_M}\right) - v + \frac{1-\gamma}{1-m} p_M, & \text{if } \frac{1-\gamma}{1-m} p_M \leq v \text{ and } m < \gamma, \\ v \ln\left(\frac{v}{p_M}\right) - v + p_M, & \text{if } p_M \leq v \text{ and } m \leq \gamma, \\ 0, & \text{otherwise}. \end{cases} \tag{5}$$

which is nonnegative in every case. The total sum of net utility of users is:

$$U_M = \begin{cases} p_M\left(1 - \frac{p_M}{4}\right) - \frac{1}{2}\ln(p_M) - \frac{3}{4}, & \text{if } m \leq \gamma, \\ \frac{1-\gamma}{1-m} p_M \left(1 - \frac{1-m}{1-\gamma} \frac{p_M}{4}\right) - \frac{1}{2}\ln\left(\frac{1-m}{1-\gamma} p_M\right) - \frac{3}{4}, & \text{if } m > \gamma \end{cases} \tag{6}$$

Equation (6) is derived from integral of (5) in $[p_M, 1]$ when m is greater than γ, and $[\frac{1-\gamma}{1-m} p_M, 1]$ when m is lower or equal to γ with respect to willingness to pay v.

4.2 MO's Pricing and Mining

MO determines price p_M and the computing resource for PoW m to achieve the maximum profit. Consider m is divided by two cases: the one is less or equal than redundant computing resource for providing service γ, the other is greater than γ.

- Case $m \leq \gamma$: Since MO's involvement in the blockchain does not affect services, MO's profit is the maximum when m is equal to γ. Thus, problem (1) is replaced by the follow problem:

$$\max_{0 \leq p_M \leq 1} \pi^{MO}(p_M) = \max(p_M - p_s) Q(p_M) + \gamma p_w. \tag{7}$$

Since the bandwidth that can be provided by MNO is W, the overall optimization problem is as follows:

$$\max_{0 \le p_M \le 1} \pi^{MO}(p_M) = max(p_M - p_s)Q(p_M) + \gamma p_w,$$
$$subject\ to \quad Q(p_M) \le W. \tag{8}$$

Given demand of users as (4), the total demand of shared spectrum in the MO network is derived as follows

$$Q(p_M) = \int_{P_M}^{1} \left(\frac{v}{p_M} - 1 \right) dv = \frac{1}{2p_M} - 1 + \frac{p_M}{2}, \tag{9}$$

where Q_M is decreasing function in $p_M \in [0, 1]$.

Note that the user only uses the service when the price of service is less or equal than willingness to pay of user. The optimal solution of the above profit maximization problem is described in the following proposition.

Proposition 1. The optimal service price p_M is

$$p_M(p_s) = \frac{1}{3}\left(1 + \frac{p_s}{2}\right)\left(1 + 2\cos\left(\frac{\phi + 4\pi}{3}\right)\right),$$

where $\phi = \tan^{-1}\left(\frac{\sqrt{p_s\left(\frac{2}{27}\left(1+\frac{p_s}{2}\right)^3 - \frac{p_s}{4}\right)}}{\frac{2}{27}\left(1+\frac{p_s}{2}\right)^3 - \frac{p_s}{2}} \right)$ and p_s is normalized in $(p_M^3, 1]$.

Proof. See Appendix A. ■

- Case $m > \gamma$: Since MO's involvement in the blockchain affect its users utility introduced as (2). The problem of MO's profit maximization should be considered jointly with m and p_M:

$$\max_{0 \le p_M \le 1, \gamma \le m \le 1} \pi^{MO}(p_M, m) = max\ p_M Q(p_M, m) + mp_w$$
$$subject\ to \quad Q(p_M, m) \le W. \tag{10}$$

Given the demand of user of (4), the total shared spectrum demand in the MO network is calculated as

$$Q(p_M, m) = \int_{\frac{1-\gamma}{1-m}p_M}^{1} \left(\frac{v}{p_M} - \frac{1-\gamma}{1-m} \right) dv = \frac{1}{2p_M} - \frac{1-\gamma}{1-m} + \left(\frac{1-\gamma}{1-m}\right)^2 \frac{p_M}{2}. \tag{11}$$

Under certain conditions for p_w, the optimal solution of (10) is derived in the following Proposition 2.

Proposition 2. When the reward for PoW p_w is following condition $p_w > M_h$, the optimal solution p_M^* of (10) is p_w where M_h is $\frac{1}{p_M^2(1-\gamma)}$.

Proof. See Appendix B. ■

The variation of total profit of MO is greater than zero when the reward of PoW p_w is greater than M_h. According to Proposition 2, the MO abandon to providing services and allocate all computing power to PoW when p_w is greater than M_h.

Proposition 3 introduces the optimal point of objective function (10).

Proposition 3. When p_w is less than M_l, the optimal solution (p_M^*, m^*) of the objective function (10) is:

$$(p_M^*, m^*) = \left(\frac{1}{3}\left(1+\frac{p_s}{2}\right)\left(1+2\cos\left(\frac{\phi+4\pi}{3}\right)\right), \gamma\right),$$

where ϕ is $\tan^{-1}\left(\frac{\sqrt{p_s\left(\frac{2}{27}\left(1+\frac{p_s}{2}\right)^3-\frac{p_s}{4}\right)}}{\frac{2}{27}\left(1+\frac{p_s}{2}\right)^3-\frac{p_s}{2}}\right)$ and M_l is $(1-\gamma)(p_M-p_s)(1-p_M)$.

Proof. See Appendix C. ■

The variation of total profit of MO is less than zero when the reward of PoW p_w is less than M_l. From the Proposition 3, the MO would keep providing services and allocate only redundant computing power to PoW when p_w is lower than M_l.

We analyze the effects of rewards for the PoW p_w on the utility of users and MO's profit, which is divided into three cases:

- $p_w < M_l$: This case implies the rewards of the PoW are very low so that MO allocates only redundant computing power to PoW.
- $p_w > M_h$: The rewards of the PoW are considered as high price. Therefore, MO allocates its all computing power to performing PoW.
- $M_l \leq p_w \leq M_h$: MO allocates more resources than the redundant computing power to get the rewards of PoW by reducing the revenue from providing service.

Figure 3 shows the total net utility of users of MO U_M according to the rewards of PoW p_w. When p_w is lower than M_l, MO can fully focus on providing services. As p_w increase, the computing resource for PoW m is allocated by taking the portion of

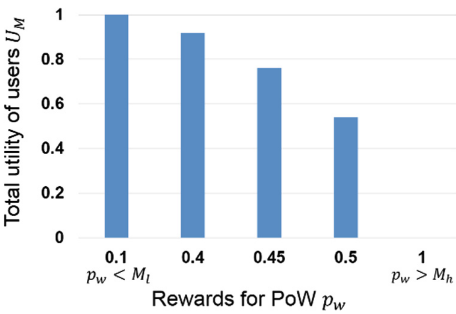

Fig. 3. The total net utility of users of MO U_M when $p_s = 0.15$ and $\gamma = 0.7$.

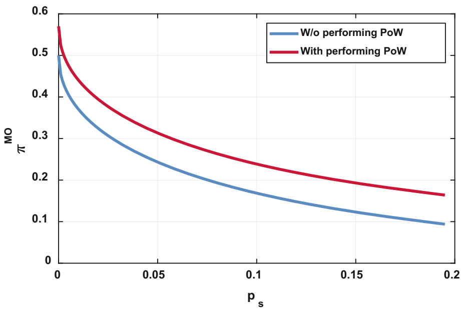

Fig. 4. MO's equilibrium profits π^{MO} depending on the unit price of leased spectrum p_s when $p_w = 0.1 < M_l$ and $\gamma = 0.7$.

computing resource for service. As a result, U_M decrease. If p_w is greater than M_h, MO only processes the PoW and the service is halted.

Figure 4 shows MO can make additional profit without affecting the total net utility through involving in the blockchain.

By setting the appropriate rewards of PoW p_w, the total users of MO utility and MO's profit can be maximized. When MOs have limited computing power, p_w is needed to be under M_l to preserve the utility of users. Otherwise, MO has no incentive for service whose profit is less than that of processing the PoW. It may disrupt the motivation of the spectrum sharing system using the blockchain networks.

5 Conclusion

In this paper, the spectrum sharing system based on blockchain network is introduced. The motivations of applying the blockchain network to the spectrum sharing system are as follow. First, the blockchain networks share database with all participants. Second, networks have mutual trust among all participants. Third, there is no need for central authority. Fourth, automated contract execution and transactions are possible.

The role of blockchain network in the Micro Operator (MO) spectrum sharing system is described. The system is designed where users of the MO receive wireless communication service via the spectrum leased from the Mobile Network Operator (MNO). The roles and functions are introduced by matching the subjects constituting the actual wireless communication network to the blockchain network.

The utility of users and the profit of MO are analyzed in economic perspective. The MO can achieve its profit not only from providing wireless communication service to users, but also from processing PoW which is essential procedure for maintaining the blockchain. By setting the appropriate PoW rewards, the total utility of users and MO's profit can be maximized. Note that too high PoW rewards can disrupt the motivation of the MO to provide wireless communication services. In worst case, MO halt providing wireless communication service to users.

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Appendix

A. Proof of Proposition 1

To find the equilibrium price $p_M^*(p_s)$, it is verified that the objective function of (7) should be a concave function of $p_M(p_s)$. Differentiate (7) is as follow:

$$\frac{\partial^2 \pi^{MO}}{p_M(p_s)^2} = 1 - \frac{p_s}{p_M^3} < 0, \textit{if } p_M^3 < p_s. \tag{12}$$

Concavity of (7) for $p_M(p_s)$ is guaranteed in $p_s \in (p_M^3, 1]$. The equilibrium price can be obtained by solving the first order derivative of (7) as follows:

$$\begin{aligned} \frac{\partial \pi^{MO}}{\partial p_M(p_s)} = p_M(p_s) - 1 - \frac{p_s}{2}\left(1 - \frac{1}{p_M(p_s)^2}\right) = 0 \\ 2p_M(p_s)^3 - (2 + p_s)p_M(p_s)^2 + p_s = 0 \end{aligned} \tag{13}$$

Finally, three candidate solutions to maximize MO's profit as follows:

$$p_M(p_s) = \frac{1}{3}\left(1 + \frac{p_s}{2}\right)\left(1 + 2cos\left(\frac{\phi + 2n\pi}{3}\right)\right), \textit{where } n \in \{1, 2, 3\}. \tag{14}$$

There is a unique optimal solution when $n = 3$ because $p_M(p_s)$ is either 1 or negative when $n = 1$ or $n = 2$. ■

B. Proof of Proposition 2

The first order partial derivative of the objective function of (10) respect to m is

$$\frac{\partial \pi^{MO}}{\partial m} = p_w + (p_M - p_s)\left(\frac{p_M(1-\gamma)^2}{(1-m)^3} - \frac{1-\gamma}{(1-m)^2}\right) \tag{15}$$

If the Eq. (15) is greater than 0 for all m, the objective function has the maximum value when m is maximum, that is, when $m = 1$.

If $p_w > \frac{1}{p_M^2(1-\gamma)}$, the Eq. (15) has following relationship:

$$\frac{\partial \pi^{MO}}{\partial m} > \frac{1 - (p_M - p_s)}{p_M^2(1-\gamma)} + (p_M - p_s)\left(\frac{1}{p_M^2(1-\gamma)} - \frac{1-\gamma}{(1-m)^2}\right) \cdots (*) \tag{16}$$

Note that the function $\frac{1-\gamma}{(1-m)^2}$ is an increasing function for m. Substitute m with the value $1 - p_M(1-\gamma)$ which is maximum value of m then the Eq. (16) is

$$\begin{aligned} (*) &> \frac{1 - (p_M - p_s)}{p_M^2(1-\gamma)} + (p_M - p_s)\left(\frac{1}{p_M^2(1-\gamma)} - \frac{1-\gamma}{(p_M(1-\gamma))^2}\right) \\ &= \frac{1 - (p_M - p_s)}{p_M^2(1-\gamma)} > 0 \end{aligned} \tag{17}$$

Finally, $\frac{\partial \pi^{MO}}{\partial m} > 0$ for all m when $p_w > \frac{1}{p_M^2(1-\gamma)}$. ■

C. Proof of Proposition 3

The first order partial derivative of (10) respect to m is (18).

$$\begin{aligned}\frac{\partial \pi^{MO}}{\partial m} &= p_w + (p_M - p_s)\frac{1-\gamma}{(1-m)^2}\left(\frac{1-\gamma}{1-m}p_M - 1\right) \\ &< (p_M - p_s)\frac{1-\gamma}{(1-m)^2}\left((1-m)^2 + \left(1 - \frac{1}{1-m}\right)\frac{1-\gamma}{1-m}p_M - 1\right)\cdots(**)\end{aligned} \tag{18}$$

The Eq. (18) is negative when $m \geq \gamma$ and $0 < m < 1$.
Finally, $\frac{\partial \pi^{MO}}{\partial m} < 0$ for all m when $p_w < (1-\gamma)(p_M - p_s)(1 - p_M)$. ■

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